PROPERTIES OF SOLIDS

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11.3 Band Theory of Solids

The information of the band of energy levels of solids can be clearly illustrated in terms of the 'molecular orbital theory'.

The salient features of band theory of solids are as follows:

1. Materials in the solid state do have very large aggregation of atoms (or ions) and are arranged in regular close-packed structures.
2. The constituents (ions or atoms) of solids are bound together by a cohesive force and as a result, the atomic orbitals of valence electron shells interact and overlap with each other and give rise to 'molecular orbitals'.

When two atomic orbitals (half-filled) overlap, two molecular orbitals of different energy levels are formed as shown in Fig. 11.1.

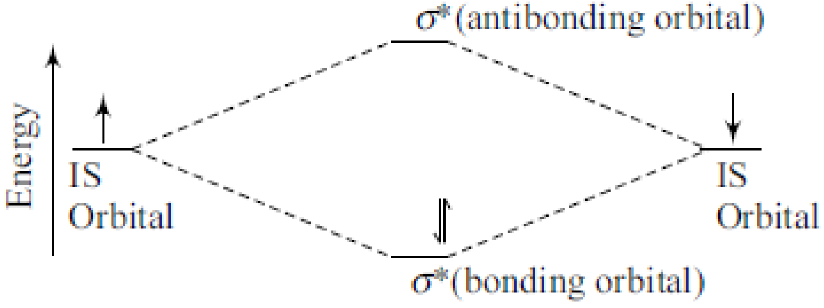

Figure 11.1 *Overlap of two molecular orbitals (MO).*

It can be visualized that one of the molecular orbitals (MO) gets stabilized due to pairing up of electrons and acquires lower energy state, which is called 'bonding molecular orbital' (BMO), while the other empty molecular orbital is destabilized (higher energy) and is known as 'antibonding molecular orbital' (ABMO).

When a 2*N* number of valence atomic orbitals of constituent atoms (or ions) overlap with each other in solids, they give rise to the '*N*' number of closely spaced bonding molecular orbitals and as well to '*N*' number of antibonding molecular orbitals.

For very large aggregation of atoms (or ions), a very closely spaced energy levels (σMOs and σ^*MOs) of extremely small energy difference results in the formation of 'bands' in solids and evidently, these 'energy bands' appear to be continuous as shown in Fig. 11.2.

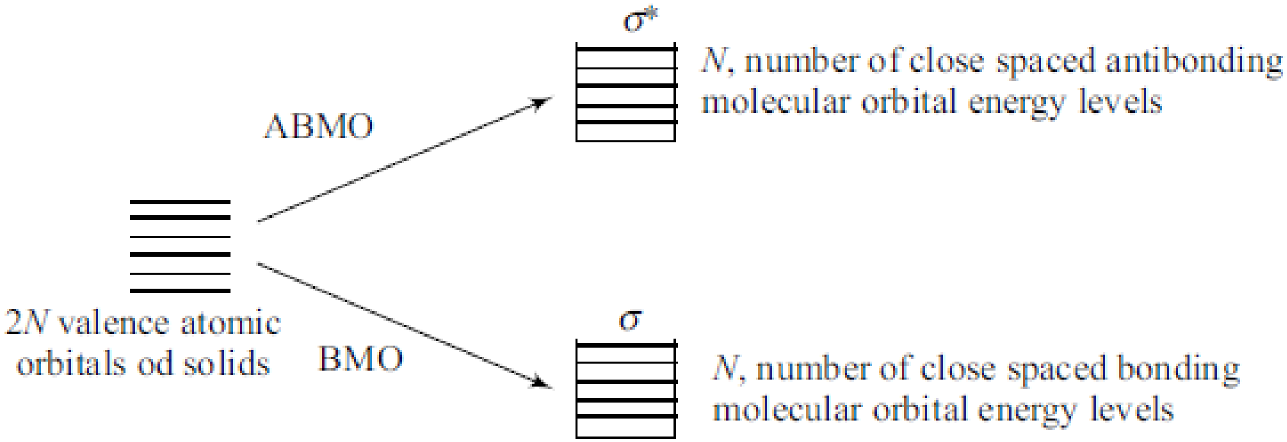

Figure 11.2 *Formation of energy bands in solids.*

The energy gap between the ABMO and BMO (i.e. σ^* and σ bands) or the magnitude of the separation of these bands depends on the nature of the constituents, the internuclear distances of atoms (ions) and the orientation of the valence electron orbitals in a particular crystal structure.

However, in few cases, the energy bands of atoms in solid may also overlap and gives rise to a continuous half-filled energy bands.

A 'band' is a group of infinitesimal energy levels in a solid.

11.4 Types of Energy Bands

The composition, electronic configuration of constituents and the structure of crystals/solids give rise to two kinds of energy band models.

11.4.1 Overlapping Energy Bands

For a particular crystal type, the higher energy band of the solid overlaps the lower energy band to some extent, as shown in Fig. 11.3.

Beryllium and magnesium are metals because the empty np° energy band overlaps the lower filled ns^2 energy band in both the cases.

11.4.2 Nonoverlapping Energy Bands

In many solids, the higher empty energy band does not overlap the lower filled (or half-filled) energy level band and evidently, there is an energy gap between the two bands of energy levels. This energy gap is known as 'forbidden energy gap' (Fig. 11.4).

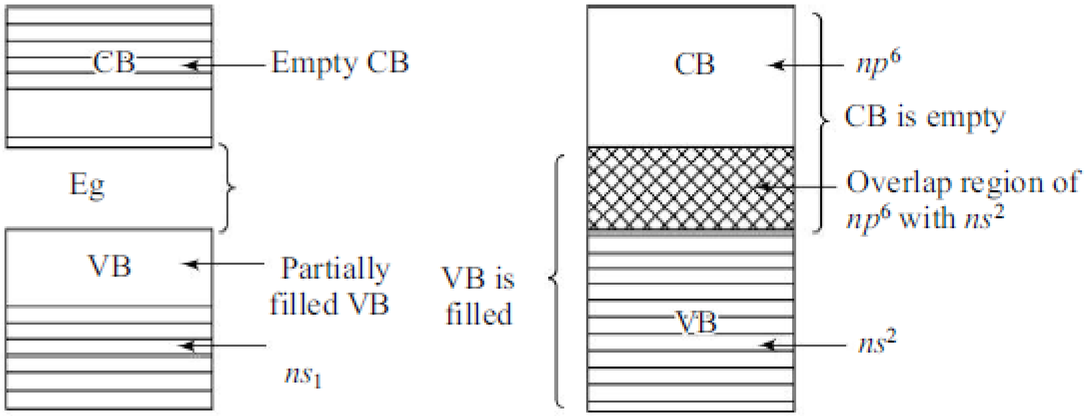

Figure 11.3 *Overlapping energy bands.*

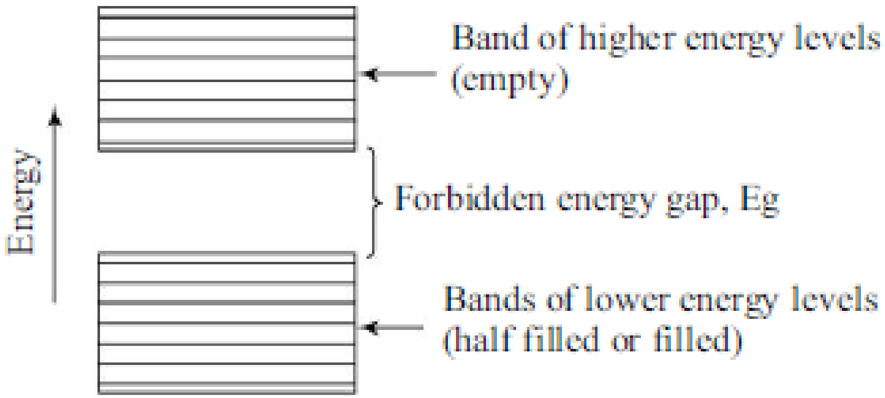

FIGURE 11.4 *Nonoverlapping energy bands.*

The energy level bands of Li, Na and Cu metals are shown in Fig. 11.5. They are good conductors due to half-filled (ns^1) lower energy band (Fig. 11.5).

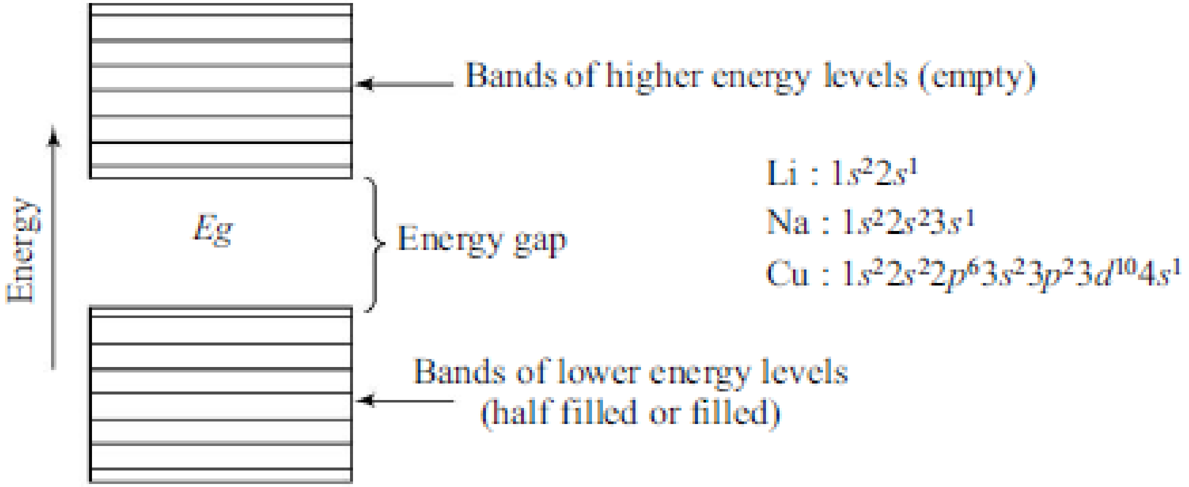

FIGURE 11.5 *Energy bands of Li, Na and Cu.*

11.4.3 Valence Band

A band of stabilized lower energy levels occupied by the valence electrons of the solid is called the 'Valence band', (VB) and obviously it is the highest filled state of a band. As shown in Fig. 11.6.

The valence band of a solid may be either (i) partially filled or (ii) completely filled with electron depending on the electronic configuration of the constituent in the solid.

(i) The 'valence band' of solids, especially in Be ($1s^2\ 2s^2$) and Mg ($1s^2\ 2s^2\ 2p^6\ 3s^2$), is completely filled with ns^2 electrons.

(ii) The valence shells of Na ($1s^2\ 2s^2\ 2p^6\ 3s^1$), Al ($1s^2 2s^2 2p^6 3s^2 3p^1$) and Cu ($1s^2\ 2d^{10}\ 4s^1$) are partially filled and therefore, the valence band (VB) of these solids are partially filled with electrons.

11.4.4 Conduction Band

A band of energy levels above the valence band in solids is called 'conduction band', (CB). The conduction band is, generally empty at absolute 0 K for solids (Fig. 11.6).

At higher temperatures, CB is occupied by electrons. The electrons occupying this band are called conduction (free or delocalized) electrons.

11.4.5 Forbidden Energy Gap

An energy gap exists between the VB and CB in solids of particular types. This energy gap E_g (eV) is called the 'forbidden energy gap' as shown in Fig. 11.6.

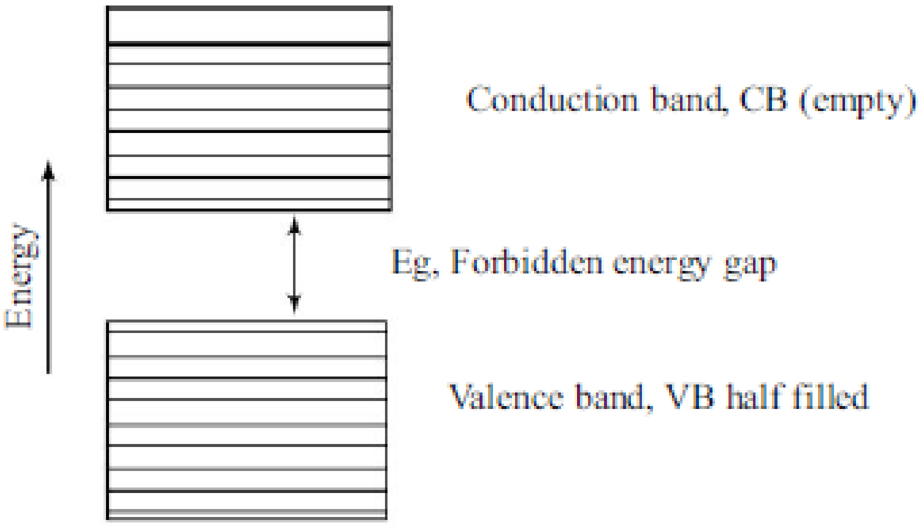

FIGURE 11.6 *Energy levels of solids indicating empty conduction band.*

(i) Conductors

Many solid-state substances are good conductors of electricity. This particular behaviour of solids can be explained in terms of 'band theory of solids'.

'A material is a good conductor if it possesses either a partially filled valence band (VB) or an empty conduction band (CB) overlaps with filled VB' (Fig. 11.7).

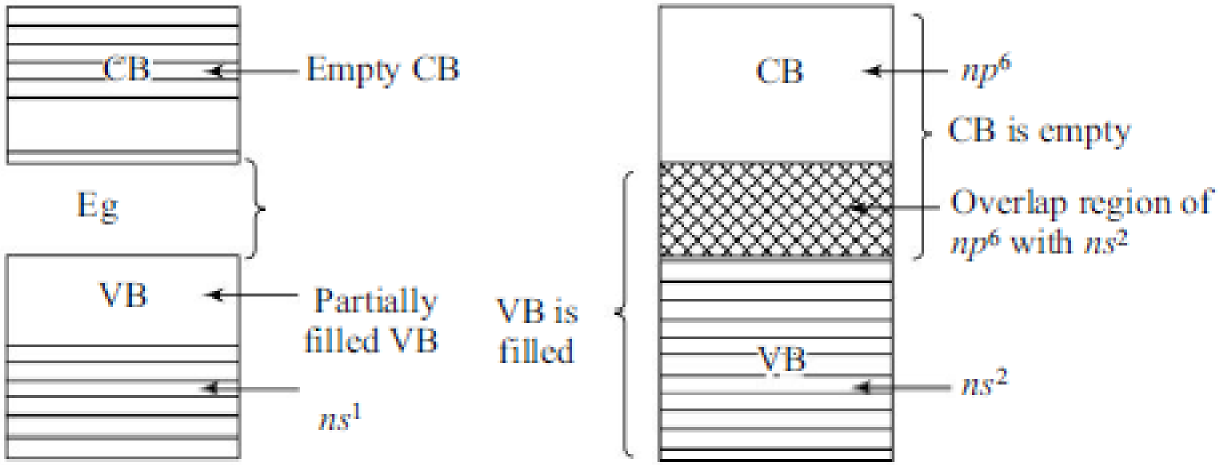

Figure 11.7 *Energy bands levels for conductors.*

In metals such as Na, Li, etc. the valence band (VB) is partially filled, with their valence electrons, ns^1 as shown in Fig. 11.7(a).

When these partially filled electrons of the VB acquire sufficient energy, they are promoted to the higher energy levels of the same VB and thus, the electrons are free to conduct electricity. Such solids behave as good conductors.

Be and Mg are metals. Both the solids have a completely filled VB with ns^2 valence electrons. The metallic properties of Be and Mg are due to the overlap of empty np^0 energy band (CB) with the completely filled VB (ns^2 electrons) as shown in Fig. 11.7(b).

A slight thermal excitation promotes these free electrons to move into different higher energy levels of the overlapped bands. Thus, Be and Mg exhibit metallic conduction.

11.5.1 Insulator

Generally, if the solids have very high value of electrical resistivities, which is greater than 10^{10} ohm cm at room temperature, then such materials is classified as 'insulators' (Fig. 11.8).

However, in terms of band theory of solids, the insulators are described in terms of the following.

(i) VB is completely filled with valence electrons.
(ii) CB is completely empty and
(iii) The forbidden energy gap, E_g between VB and CB is very large, e.g. 5–10 eV.

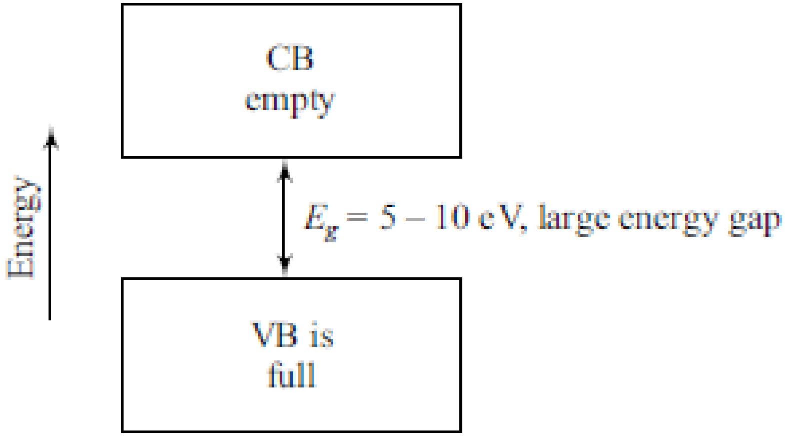

FIGURE 11.8 *Energy band levels with a wide energy gap.*

11.5.2 Semiconductors

It is found that the electrical conductivity of solid semiconductors is in between those of insulators and conductors. The electrical conductivity of these solids ranges between 1 and 10^{-8} ohm^{-1} cm^{-1} at room temperature. A solid is a semiconductor, if it satisfies the following characteristics in terms of the band theory of solids (Fig. 11.9).

(i) Almost filled VB,

(ii) Empty CB, and

(iii) A very narrow energy gap, E_g, of the order 1–2 eV

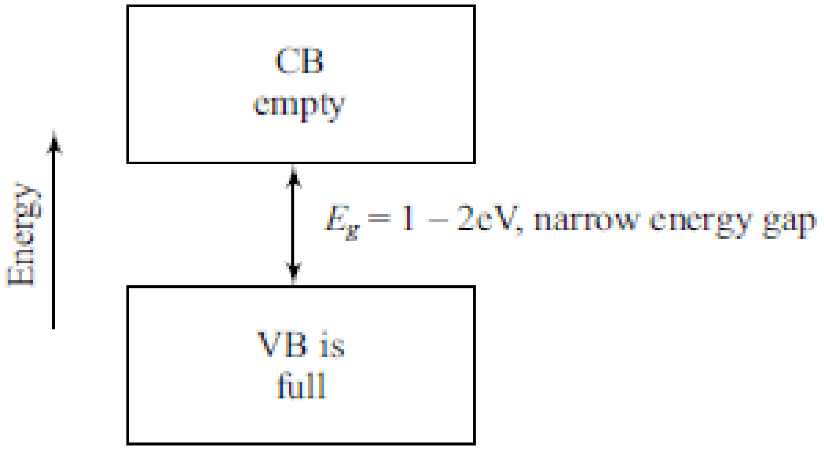

Figure 11.9 *Energy band levels of semiconductors with narrow energy gap.*

All semiconductors are insulators at 0 K. At temperatures above 0 K, thermal agitation will lift a predictable number of electrons from VB into CB, a higher energy band, since $E_g \simeq 1.0$ eV (Fig. 11.9). The electrical conductivity of semiconductors increases with the rise in temperature.

The best examples are pure elemental silicon (1.1 eV) and Ge (0.7 eV).

'Chemical impurities' and 'lattice defects' usually determine the electrical conductivity of semiconductors, which increases rapidly with temperature over certain ranges.

Oxide materials (or ceramic oxides) such as ZnO, NiO, V_2O_5 and host of others are good semiconductors with very narrow energy gaps (about 1.0 eV) due to their lattice defects.

Semiconductors are, generally, insulators at 0°C. As the temperature is raised above 0°C, thermal agitation will lift a predictable number of electrons from VB to a higher band, CB, if $E_g \sim 1.0$ eV. The electrical conductivity of semiconductors increases with the rise in temperature.

LCAO-MO THEORY OF SOLIDS

Based on the energy band structure, the arrangement of electrons and forbidden bands, solid materials are classified into the following three categories:

(1) Conductors
(2) Insulators, and
(3) Semiconductors

Conductors

Materials which conduct electric current when a potential difference is applied across them are known as conductors. In case of a conductor, the valence band is completely filled, while the conduction band is half filled.

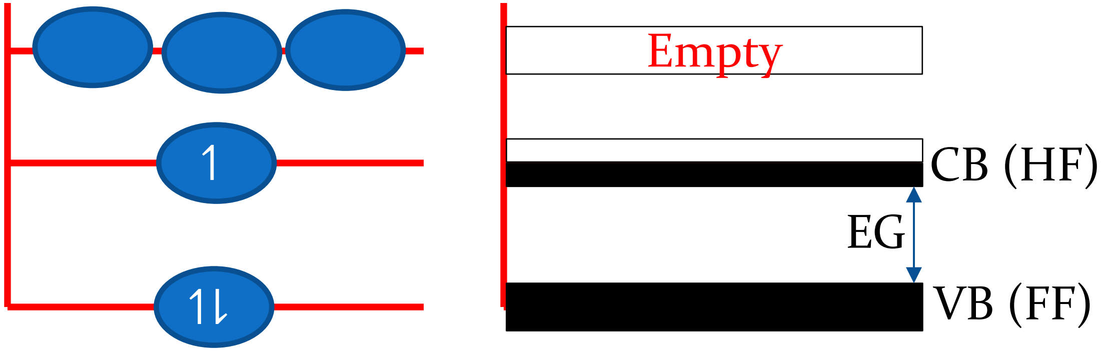

Fig. Conductor – Lithium Atom

When a small potential difference is applied to a solid material, it provides sufficient energy to the electron in the valence band to shift to the conduction band, and hence conduct electricity.

CLASSIFICATION OF SOLIDS ON THE BASIS OFBAND THEORY

Based on the energy band structure, the arrangement of electrons and forbidden bands, solid materials are classified into the following three categories:

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Conductors

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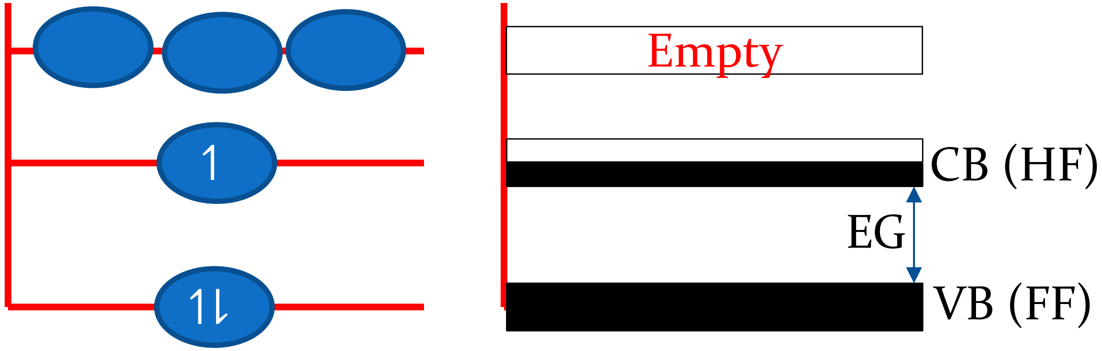


Fig. Conductor – Lithium Atom

When a small potential difference is applied to a solid material, it provides sufficient energy to the electron in the valence band to shift to the conduction band, and hence conduct electricity.

CLASSIFICATION OF SOLIDS ON THE BASIS OFBAND THEORY

Insulators

- ✓ Solid materials which do not conduct electric current under normal conditions are known as insulators.
- ✓ In insulators, the valence band is completely filled and it has no electron in the conduction band.
- ✓ Further, the forbidden energy gap will be very high when compared with a conductor.
- ✓ The energy required to shift an electron from the valence band to the conduction band in order make electrical conduction possible is very high.
- ✓ Hence, it is not possible to provide enough energy by an ordinary electric field.
- ✓ However, one can achieve electrical conduction in an insulator with very high voltage known as breakdown voltage.

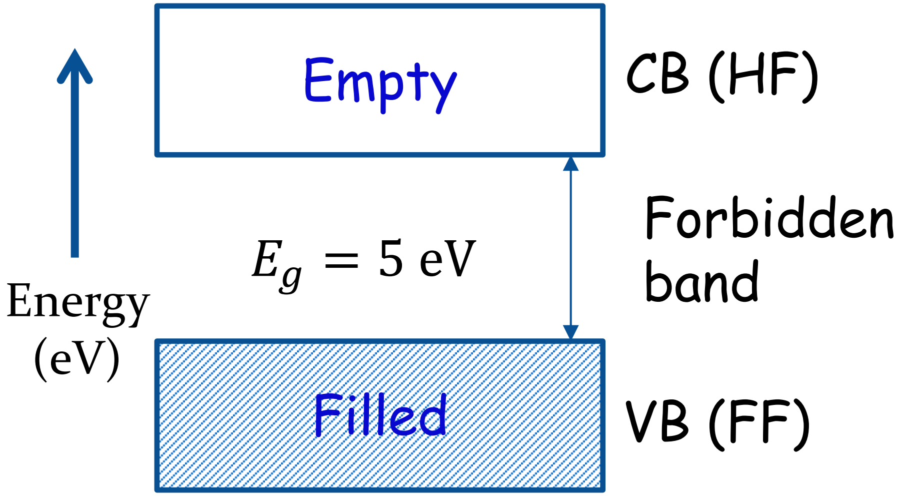


Fig. Energy bands in insulator

CLASSIFICATION OF SOLIDS ON THE BASIS OFBAND THEORY

Semiconductors

- ✓ Semiconductors are materials whose electrical conductivity lies between that of conductors and insulators.
- ✓ The conductivity of semiconductors is in the order of 10^4 to 10^{-4} mho m^{-1}.
- ✓ The magnitude of the forbidden energy gap of a semiconductor lies in between the forbidden energy gap of insulators and conductors

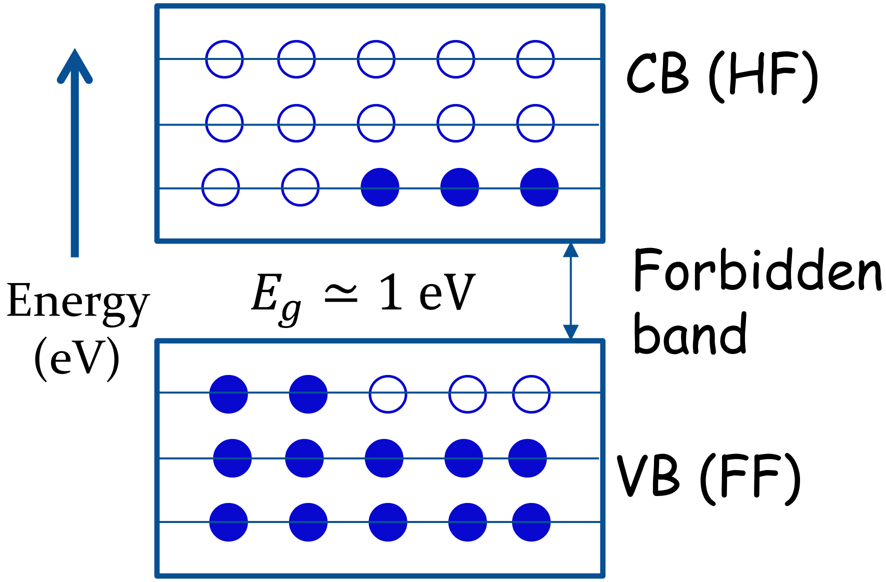
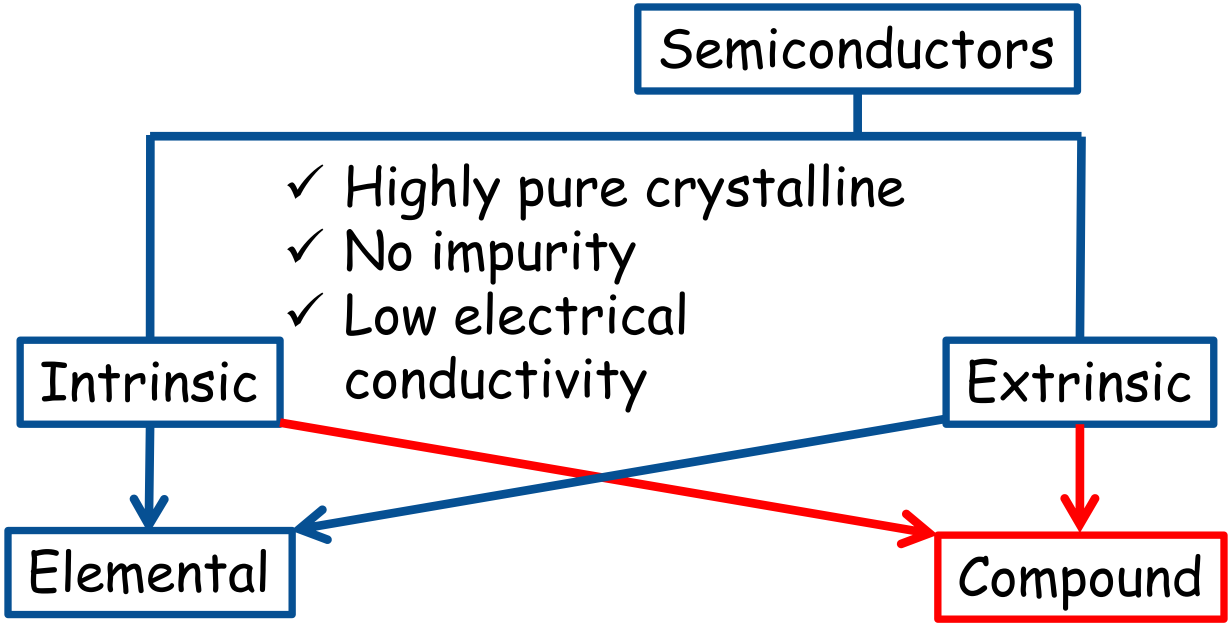


Fig. Energy bands in semiconductors

- ✓ Semiconducting materials are crystalline in nature.
- ✓ Semiconducting material may be of elemental, compound or oxide.
- ✓ Silicone and germanium are elementals semiconductors.
- ✓ GaAs, CdS, etc., are compound semiconductors
- ✓ Bi_3O_3, Te_2O_3, ZnO, etc., are oxide semiconductors

CLASSIFICATION OF SEMICONDUCTORS

Based on the concentration of electrons and holes in the materials, semiconductors are classified into two categories:



Semiconductors

Intrinsic

- ✓ Highly pure crystalline
- ✓ No impurity
- ✓ Low electrical conductivity

Extrinsic

- ✓ Pure crystalline
- ✓ Trace impurity
- ✓ High electrical conductivity

Elemental

- ✓ Single element of group IV elements
- ✓ Equal conc. of electrons and holes
- ✓ Fermi level is midway of CB & VB
- ✓ Si, Ge, etc.

Compound

- ✓ Two or more elements from different groups, such as IV-IV, III-V, II-VI and others
- ✓ Constant proportion so that average valence 4.
- ✓ GaAs, InP, InGaAs, AlInGaP, etc

PURE OR INTRINSIC SEMICONDUCTORS

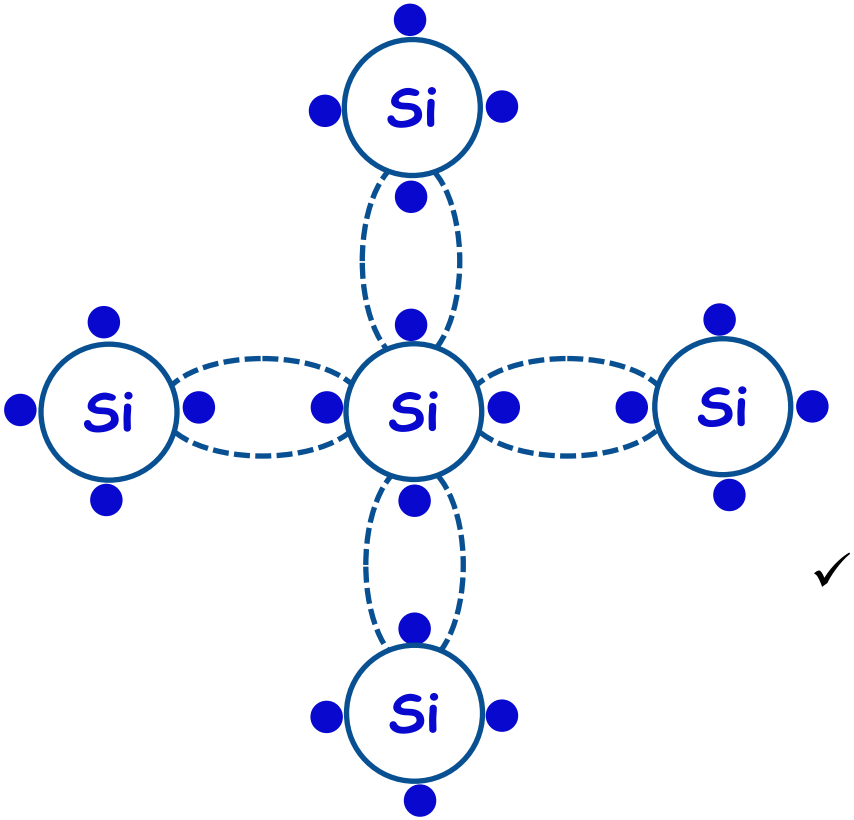


Fig. Two-dimensional arrangement of atoms in silicon at T = 0 K

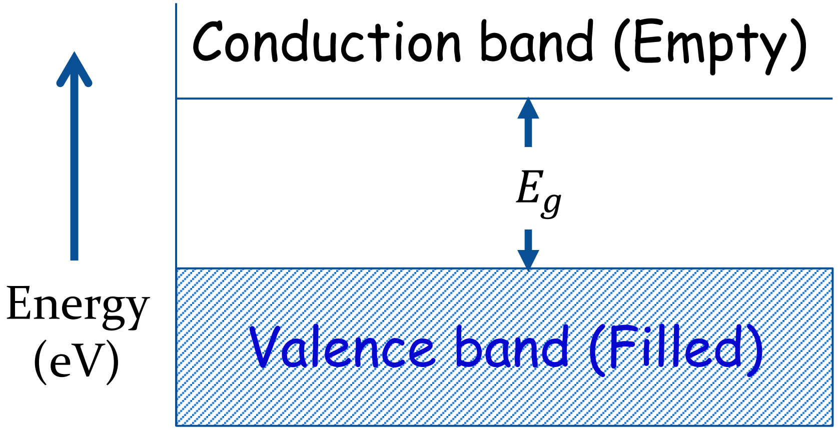


Fig. Energy band diagram of silicon atoms at T = 0 K

- ✓ At 0 K, the VB is completely filled and there is no empty space in the VB. Therefore, electrons can not shift from the VB to the CB through the forbidden gap.
- ✓ The shifting electrons is not possible even for a large applied field strength at 0 K.
- ✓ The material behaves as an insulator.

PURE OR INTRINSIC SEMICONDUCTORS

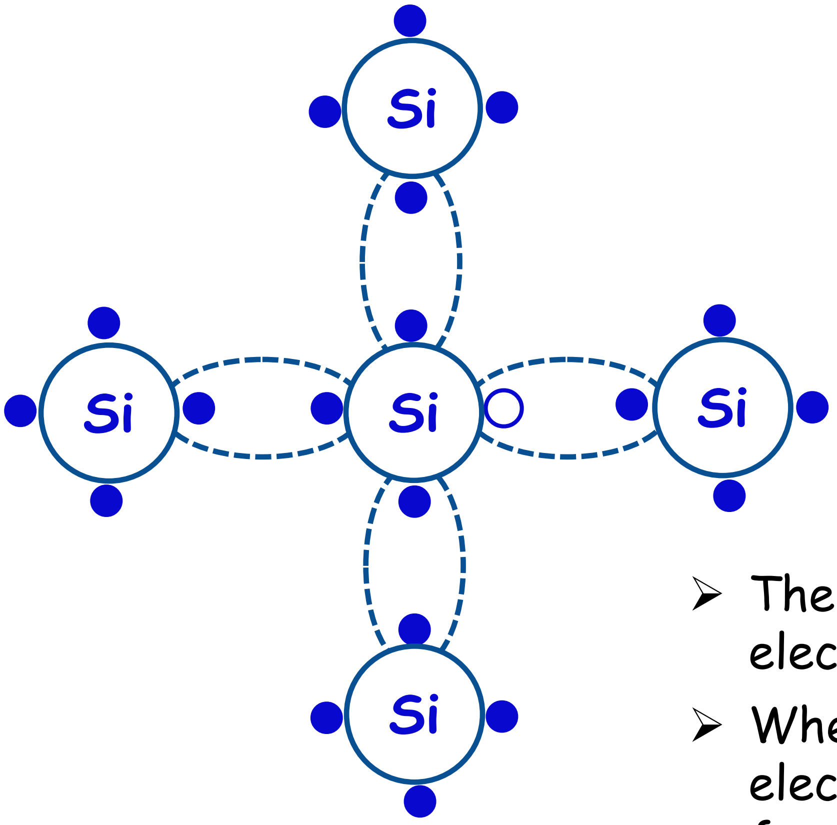


Fig. Two-dimensional arrangement of atoms in silicon at T > 0 K

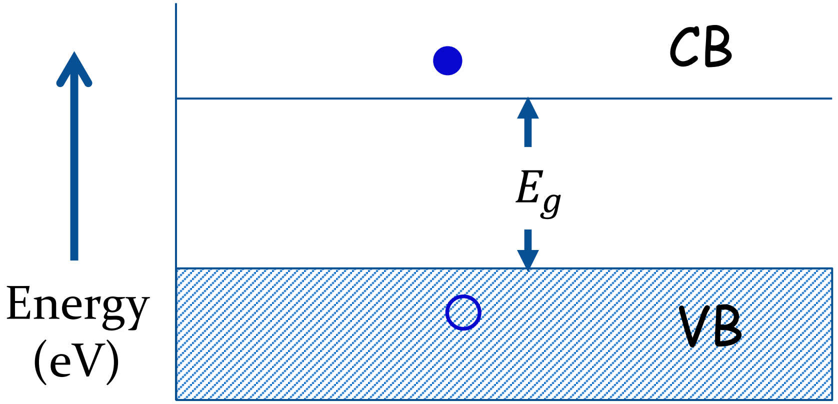


Fig. Energy band diagram of silicon atoms at T > 0 K

- The thermal energy is sufficient to liberate an electron from the VB at RT
- When an electrical field is applied, the free electron acquires sufficient energy and shifts from the VB to the CB. This results in the creation of a hole in the VB
- The free electrons move in the CB, while the holes move in the VB..
- Due to the opposite charges, the movement of electrons and holes give rise to an electric current in the same direction.

EXTRINSIC SEMICONDUCTORS

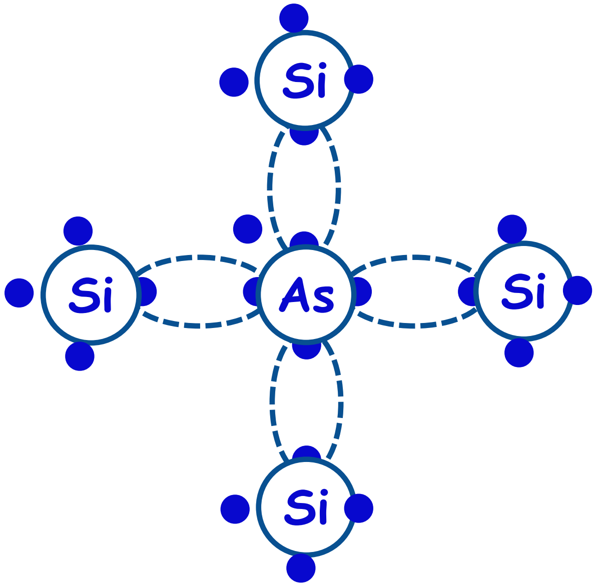
- ✓ The application of intrinsic semiconductors is restricted due to its low conductivity. In electronic devices, high conducting semiconductors are more essential. The concentration of either electrons or holes in a semiconductor is essential.
- ✓ The concentration of either electrons or holes in a semiconductor is increased depending upon the requirements in the electronic devices.
- ✓ This can be carried out simply by adding impurities (one atom in 10^7 host atoms) to the intrinsic semiconductors. The process of adding impurity to the intrinsic semiconductors is known as doping.
- ✓ The doped semiconductor is known as extrinsic semiconductor. The concentration of electrons and holes are not equal in an extrinsic semiconductor.
- ✓ Extrinsic semiconductors are classified into two categories based on the concentration of the charge carriers namely,

  (1) n-type semiconductors, and

  (2) p-type semiconductors

N-TYPE SEMICONDUCTORS

- ✓ When a pentavalent atom such as As (Sb, Bi, P) is added as a dopant to the tetravalent Si atom, the As atom will occupy one site of the Si atom.
- ✓ Thus, out of five free electrons in As, four electrons make covalent bonds with the four neighbouring Si atoms and the fifth one is loosely bound to the Si atom current in the same direction.
- ✓ The energy required to ionize the fifth electrons is very less and hence, the thermal energy of the material shifts the free electrons to the conduction band.
- ✓ Each arsenic atom contributes one free electron to the crystal and hence, it is called a donor impurity.
- ✓ In this type of semiconductor, the concentration of charge carriers (i.e., electrons) is more than that of holes.
- ✓ Therefore, these semiconductors are called n-type semiconductors. In an n-type semiconductor, electrons are the majority current carriers while holes are the minority current carriers.



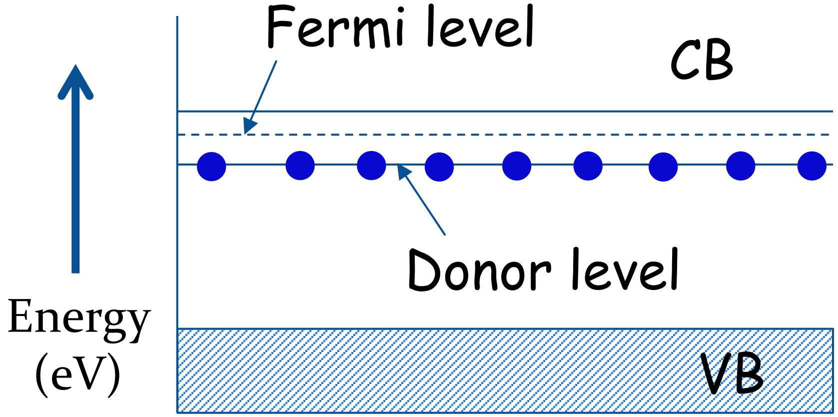


Fig. Doping in *n*-type semiconductors

P-TYPE SEMICONDUCTORS

- ✓ When a trivalent atom such as In is added as a dopant to the tetravalent Si atom, the In atom will occupy one site of the Si atom.
- ✓ The three valence electrons in indium make covalent bonds with the three neighbouring silicon atoms, whereas the fourth bond has an empty space known as hole due to the deficiency of one electron.
- ✓ Therefore, when a trivalent atom is added to silicon, it creates a hole in the valence band. The dopant (indium) accepts an electron from the neighbouring silicon atom to form a covalent bond and hence, it is called an acceptor.
- ✓ The hole in the valence band moves freely and hence, the current flows through the material. This type of electrical conduction will take place only when the dopant valency is less than that of the parent atom. Such semiconductors are called p-type semiconductors.
- ✓ In a p-type semiconductor, holes are the majority current carrier and electron are the minority current carriers.

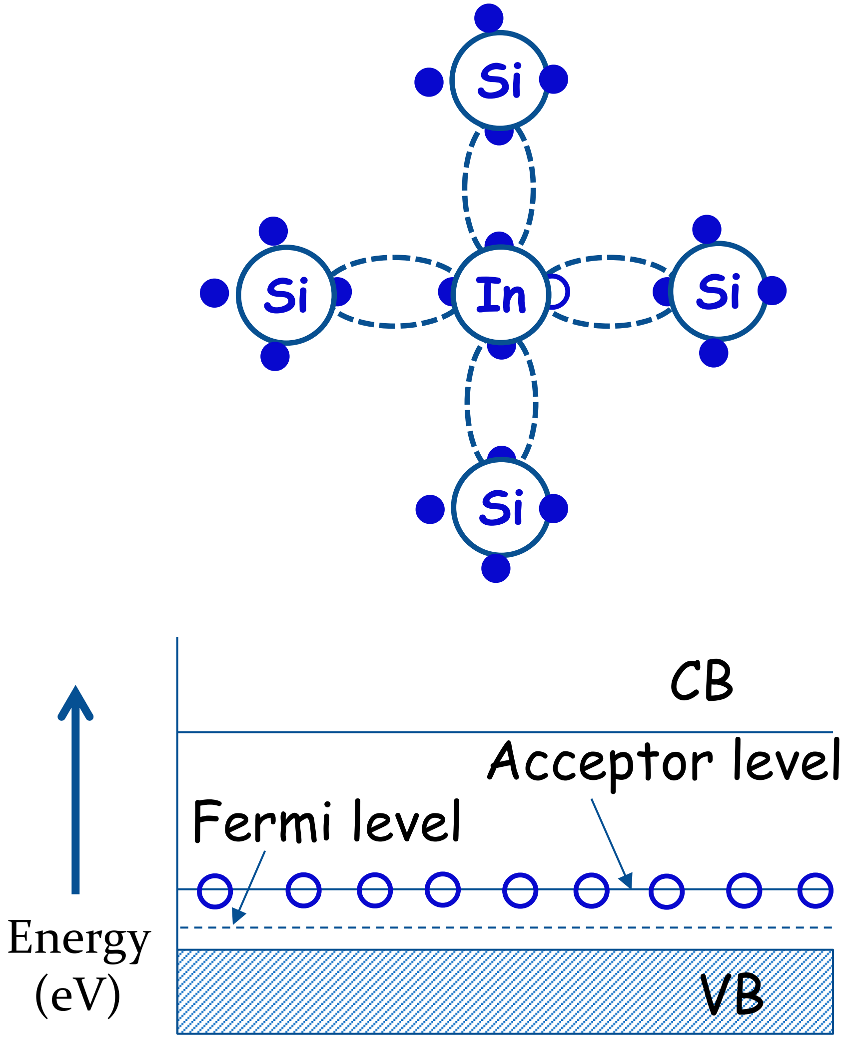
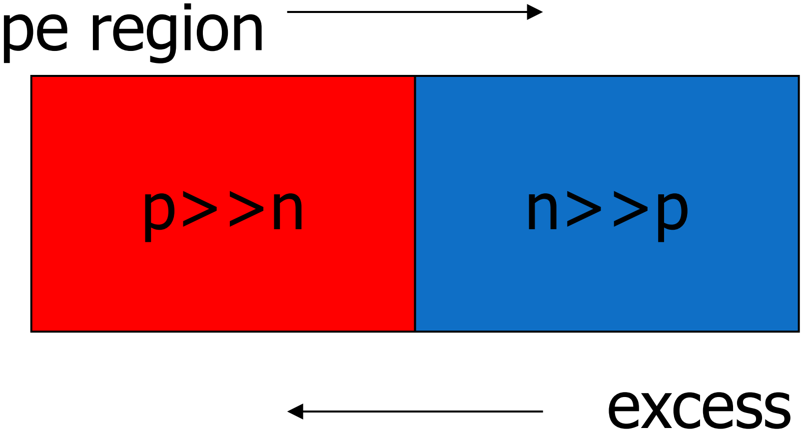


Fig. Doping in *p*-type semiconductors

DOPANT DISTRIBUTION INSIDE A PN JUNCTION

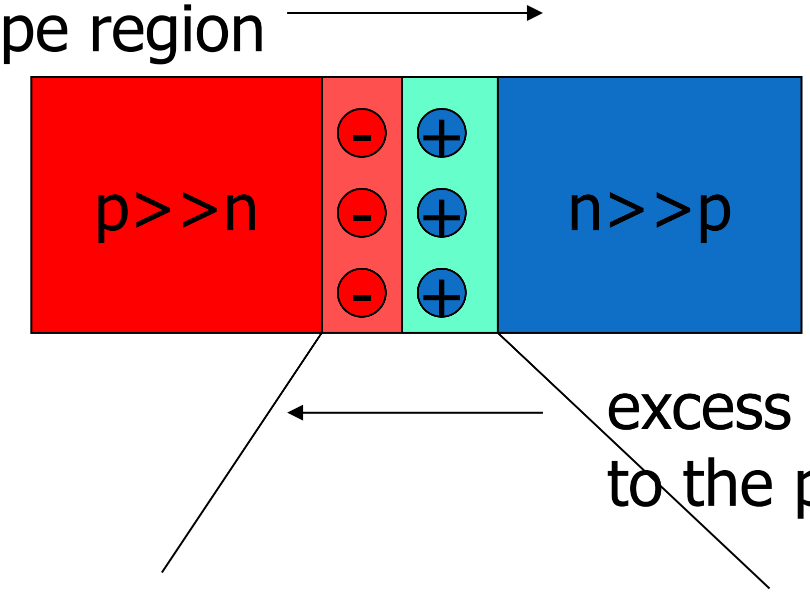
excess holes diffuse
to the n-type region



excess electrons diffuse
to the p-type region

Dopant distribution inside a pn junction

excess holes diffuse
to the n-type region



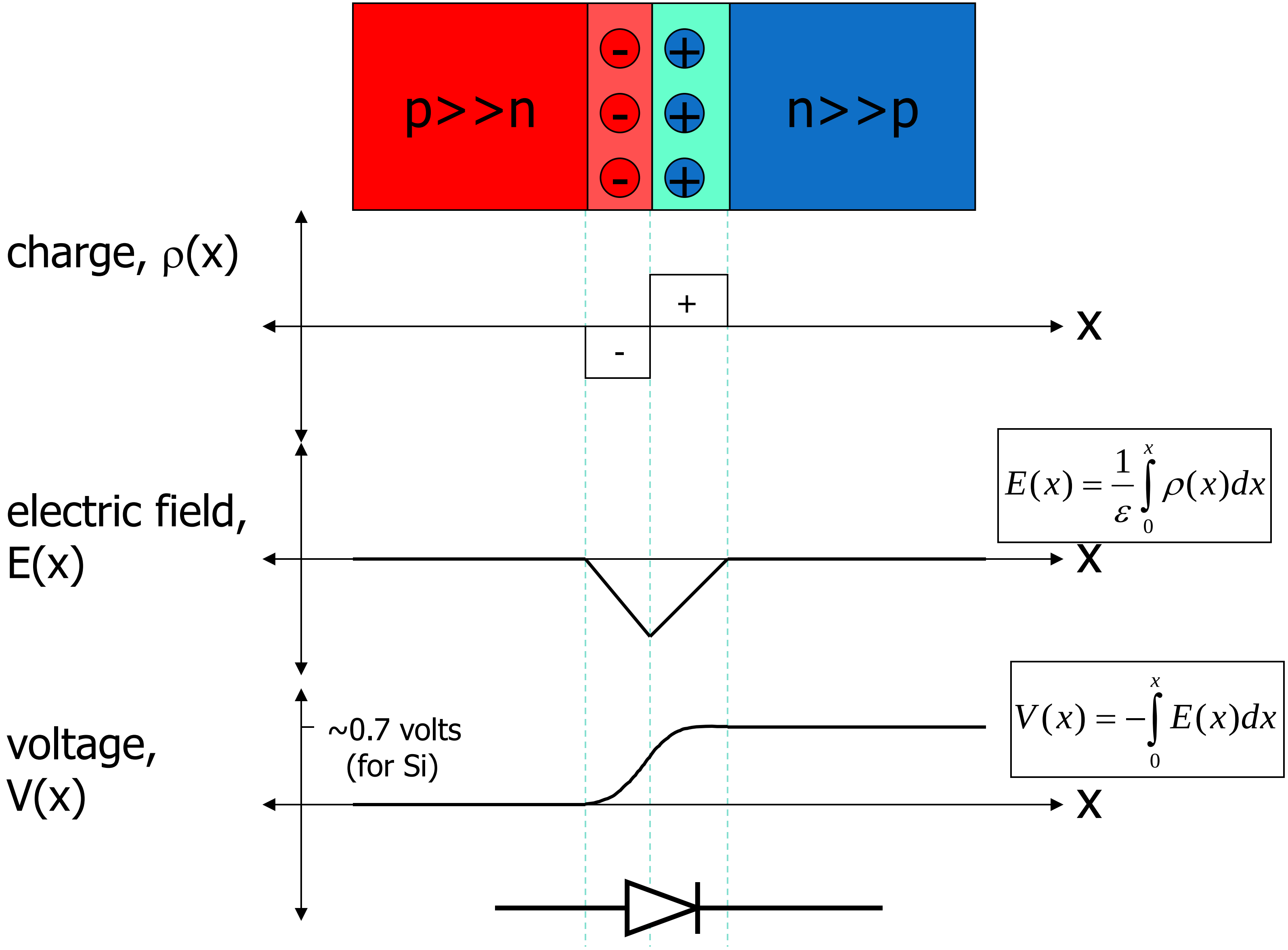
excess electrons diffuse
to the p-type region

DEPLETION REGION:

p~0, and acceptor ions are exposed ⊖

n~0, and donor ions are exposed ⊕

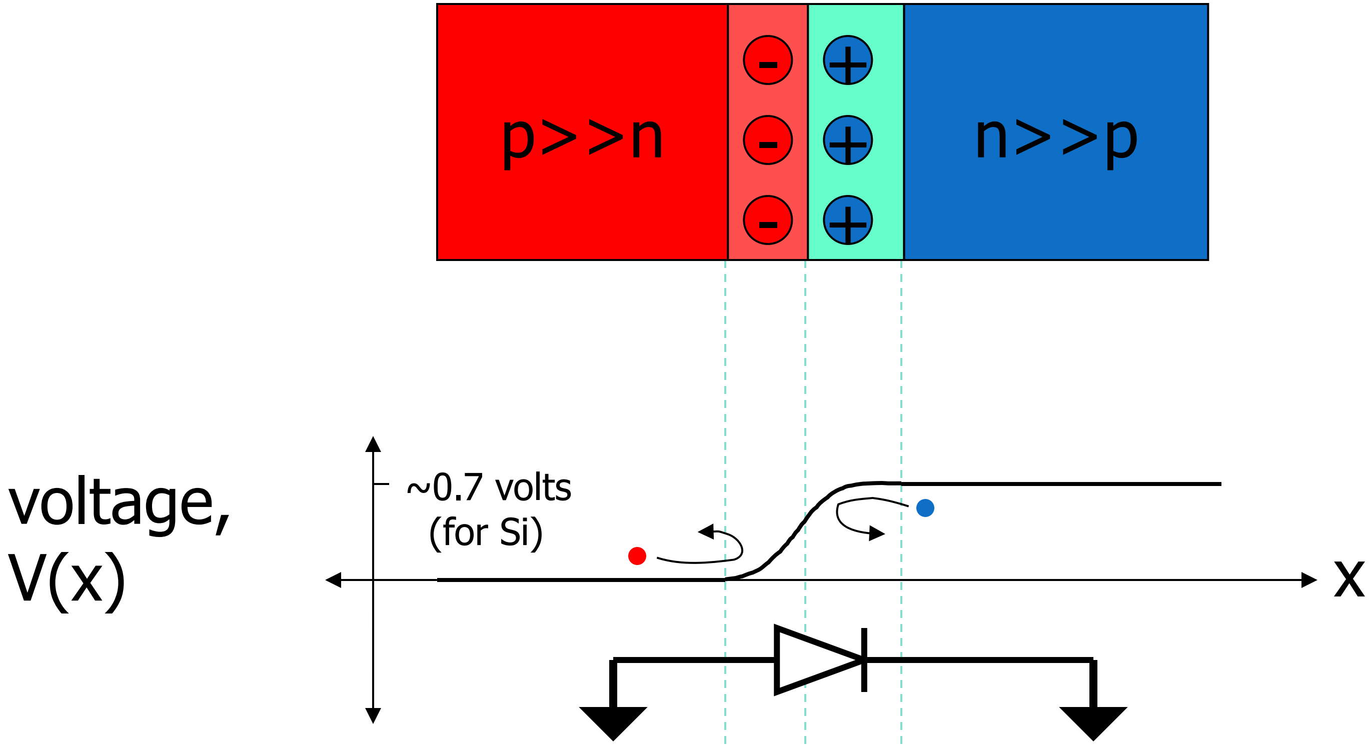
VOLTAGE IN A PN JUNCTION



$$E(x)=\frac{1}{\varepsilon}\int_0^x \rho(x)dx$$

$$V(x)=-\int_0^x E(x)dx$$

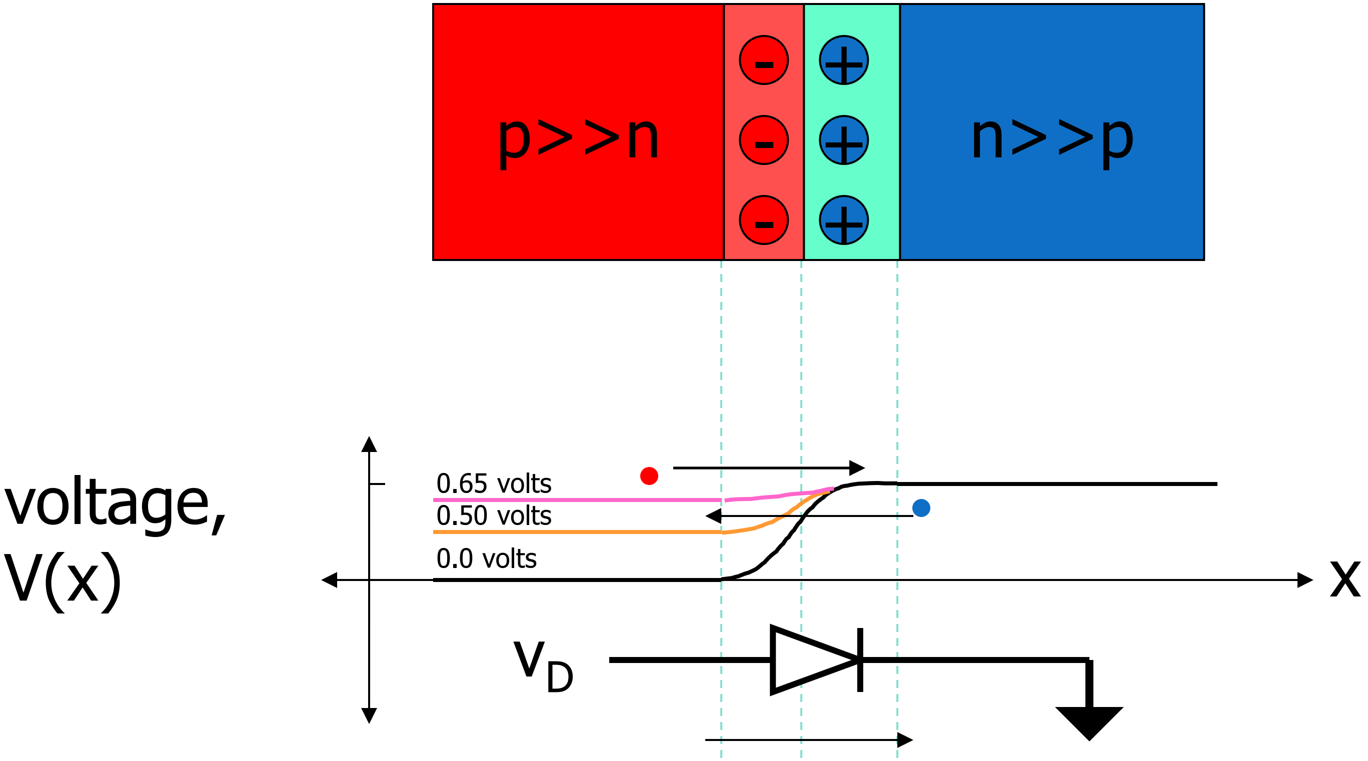
Zero Bias



At zero bias (v_D=0), very few electrons or holes can overcome this *built-in voltage barrier* of ~ 0.7 volts (and exactly balanced by diffusion)

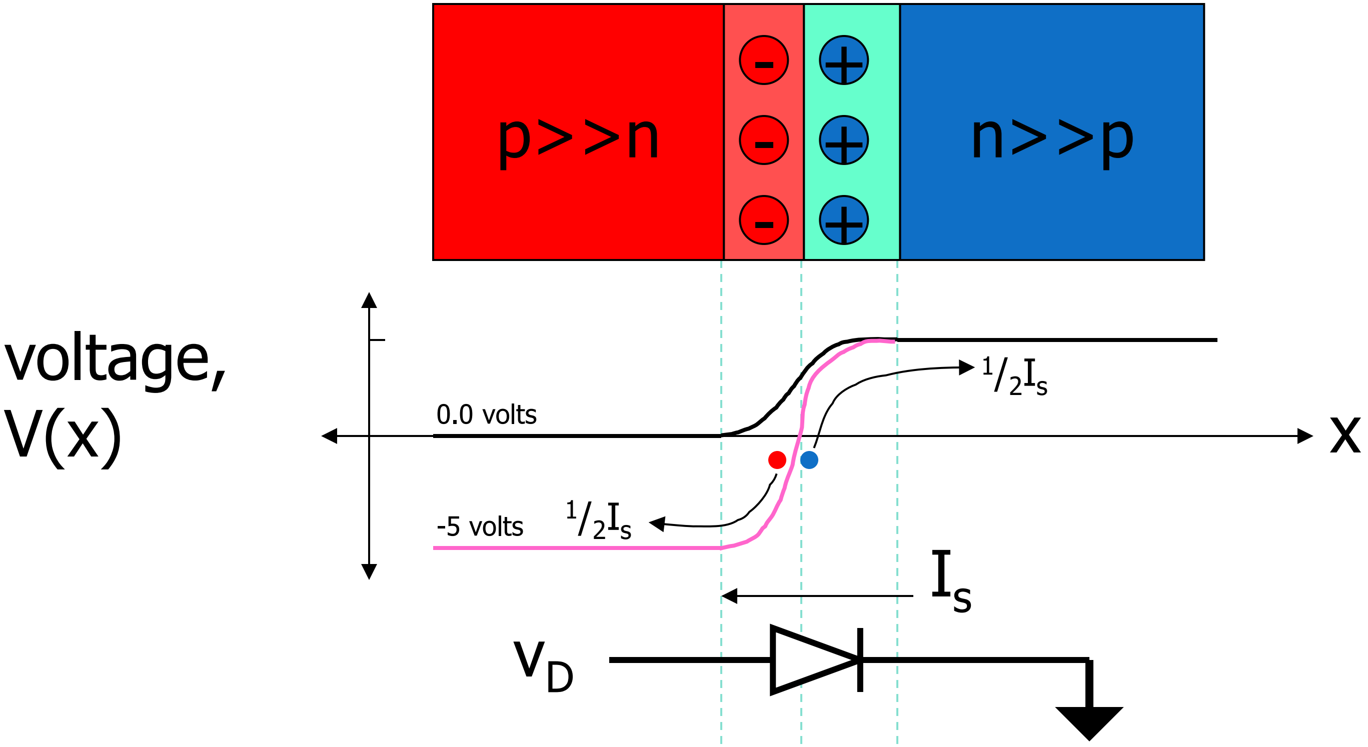
→ $i_D = 0$

Forward Bias



As the bias (v_D), increases toward 0.7V, more electrons and holes can overcome the *built-in voltage barrier* .→ $i_D > 0$

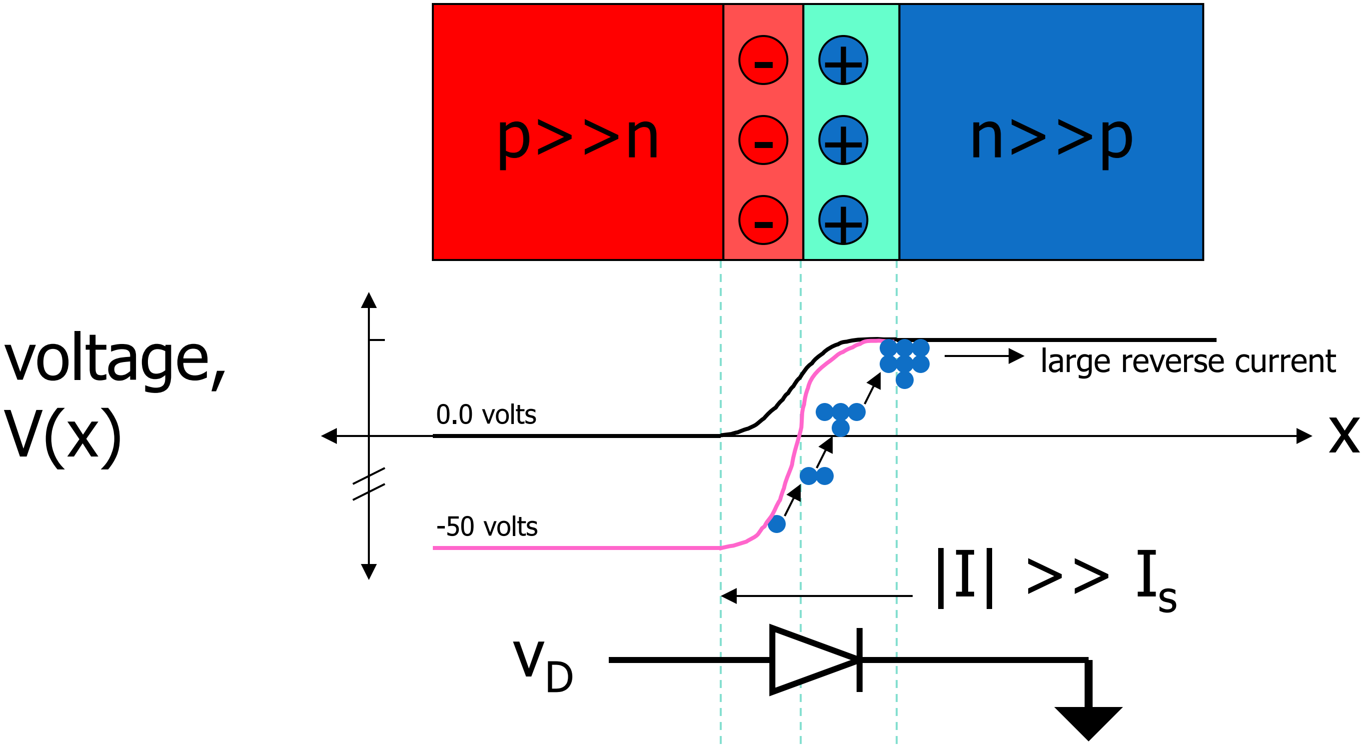
Reverse Bias



As the bias (v_D) becomes negative, the barrier becomes larger. Only electrons and holes due to broken bonds contribute to the diode current.

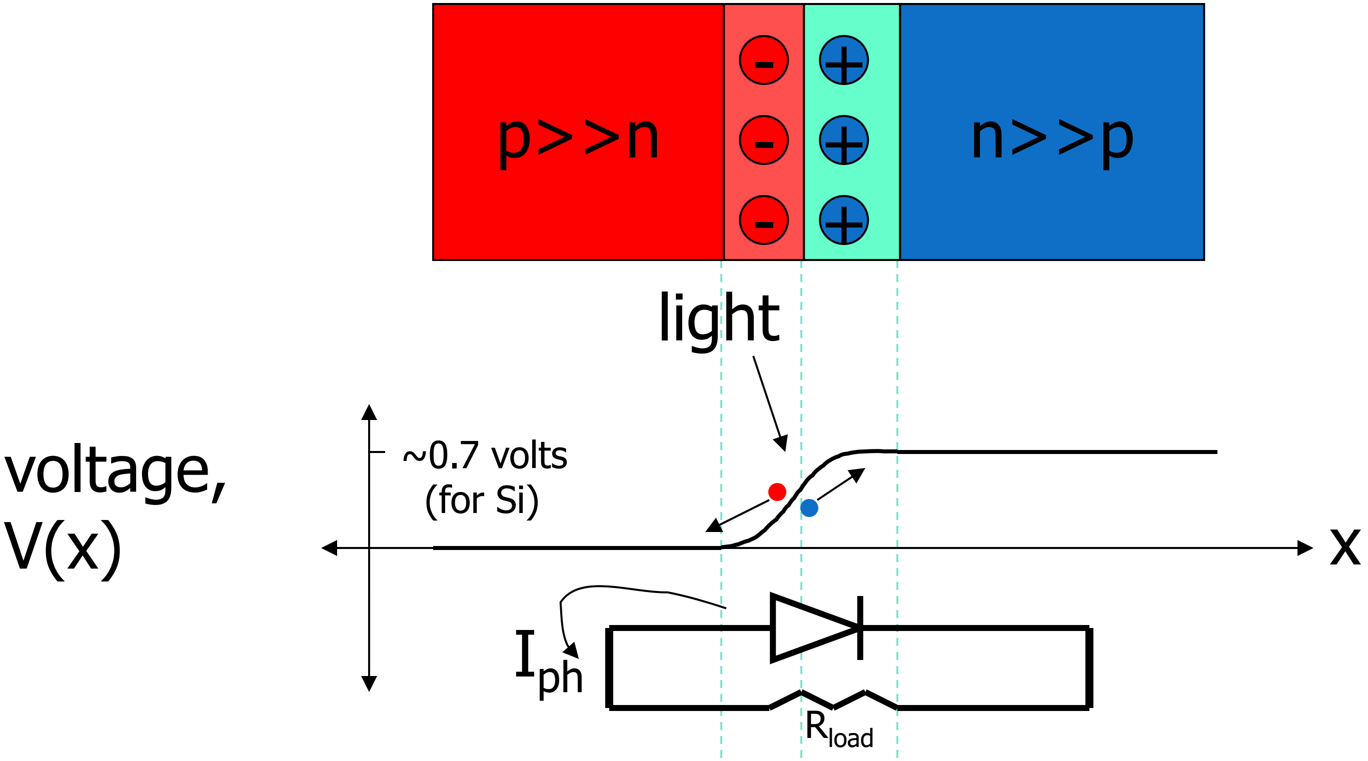
→ $i_D = -I_s$

Breakdown



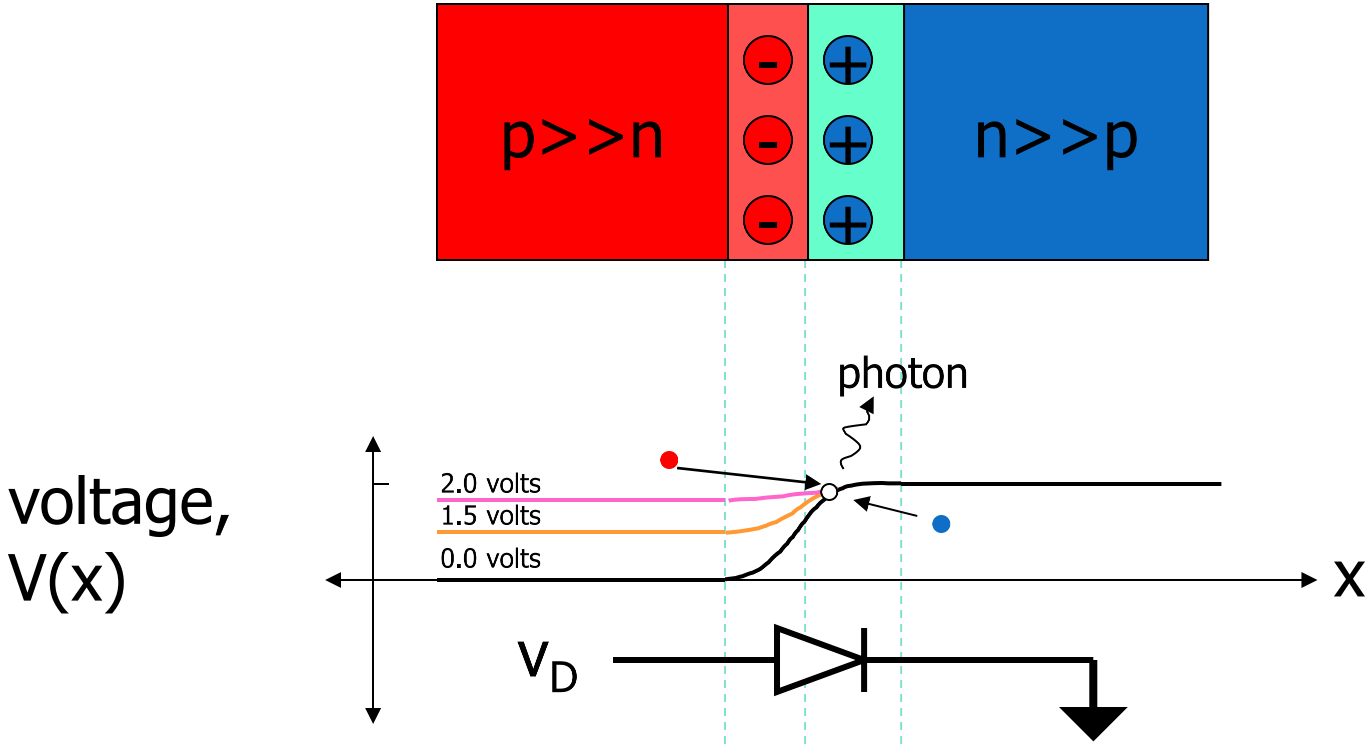
As the bias (v_D) becomes very negative, the barrier becomes larger. Free electrons and holes due to broken bonds are accelerated to high energy ($>E_g$) and break other covalent bonds – generating more electrons and holes (avalanche).

Solar Cell (Photovoltaic)



Light hitting the depletion region causes a covalent bond to break. The free electron and hole are pushed out of the depletion region by the built-in potential (0.7v).

Light Emitting Diode (LED)



In forward bias, an electron and hole collide and self-annihilate in the depletion region. A photon with the gap energy is emitted. Only occurs in some materials (not silicon).

PHOTOCONDUCTOR

What is Photoconductivity?

- ✓ Photoconductivity is an optical and electrical phenomenon in which a material becomes more electrically conductive due to the absorption of electromagnetic radiation such as visible light, ultraviolet light, infrared light, or gamma radiation.

How does photoconductivity occurs?

- ✓ When light is absorbed by a material such as a semiconductor, the number of electron hole pairs increases resulting in the increase in the number of charge carriers and raises its electrical conductivity.

PHOTOCONDUCTOR

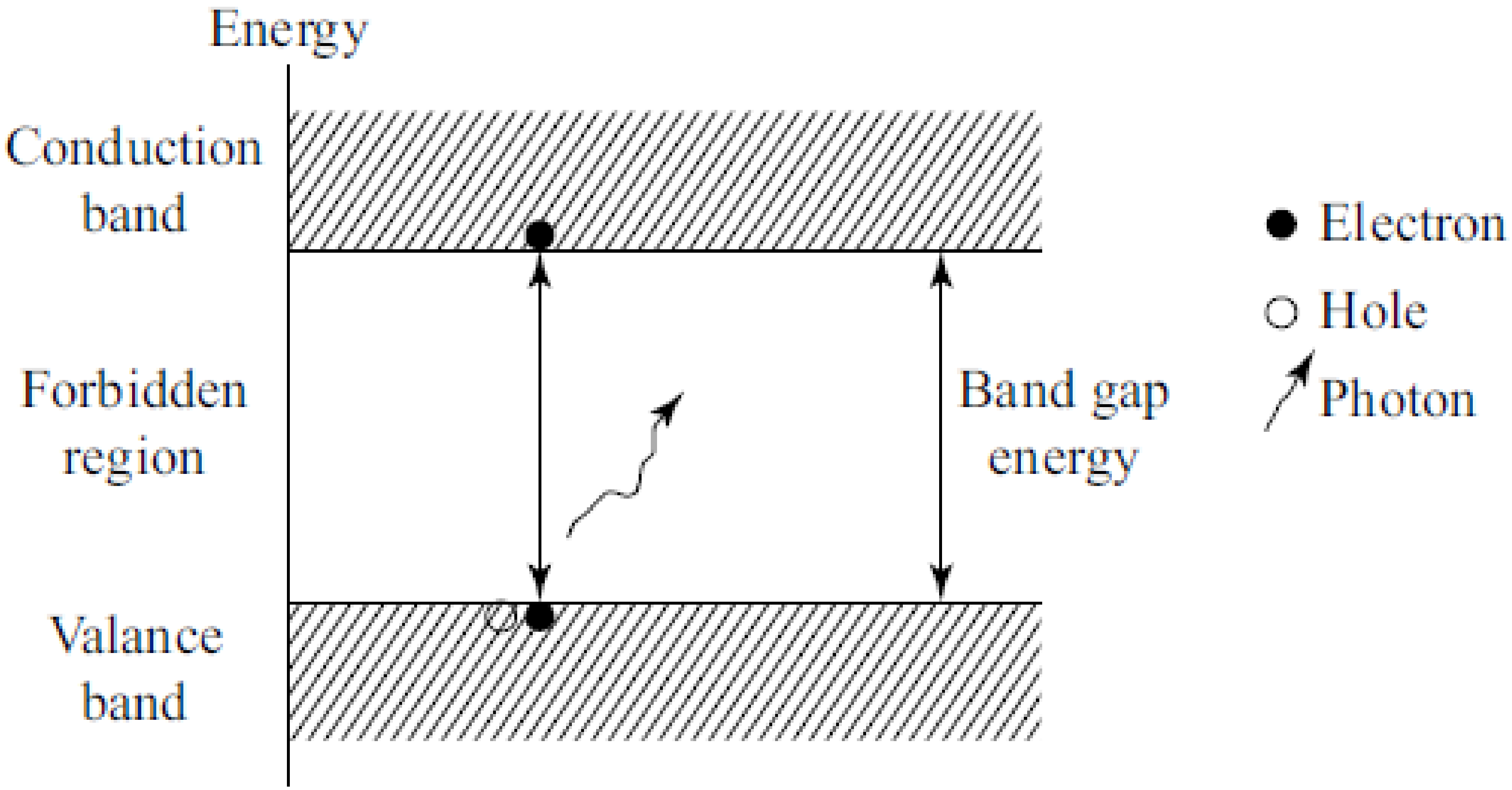


Fig. Semiconductor material electron-hole pair

PHOTOCONDUCTOR

When Photoconductivity occurs?

- ✓ To cause excitation, the photon(hv) that strikes the semiconductor must have enough energy to raise electrons across the band gap, or to excite the impurities within the band gap(E_g)
- ✓ If E_g be the minimum band gap, then the longest wavelength which may cause this effect is

$$\lambda = \frac{hc}{E_g}$$

- ✓ In a homogeneous material, the increase in conductivity when exposed to electromagnetic waves is

$$\Delta\sigma = e(\Delta n \cdot \mu_n + \Delta p \cdot \mu_p)$$

PHOTOCONDUCTOR

What are Characteristic Parameters ?

(1) Photoresponsivity

$$R = \frac{\text{Photocurrent}, i_p}{\text{Incident optical power}, P_{opt}}$$

$$= \eta \frac{\lambda(\mu m)}{1.24}\left(\frac{\tau}{t}\right)$$

where, η is the quantum efficiency $= \dfrac{\text{No. of electrons produced}}{\text{No. of incident photons}}$

λ is the wavelength of incident photon (μm)
τ is the carrier recombination time
t is the carrier transit time
$\frac{\tau}{t}$ is called Photoconductive Gain, $G = \dfrac{\tau_e(\mu_e+\mu_p)V}{L}$

PHOTOCONDUCTOR

What are Characteristic Parameters ?

(2) Spectral response

- ✓ The variation of photoconductivity with photon energy is known as spectral response.
- ✓ The maximum value of photocurrent corresponds to band gap energy and spectral response.
- ✓ The energy ranges from 3.7 eV for ZnS to 0.2 eV for cooled PbSe.

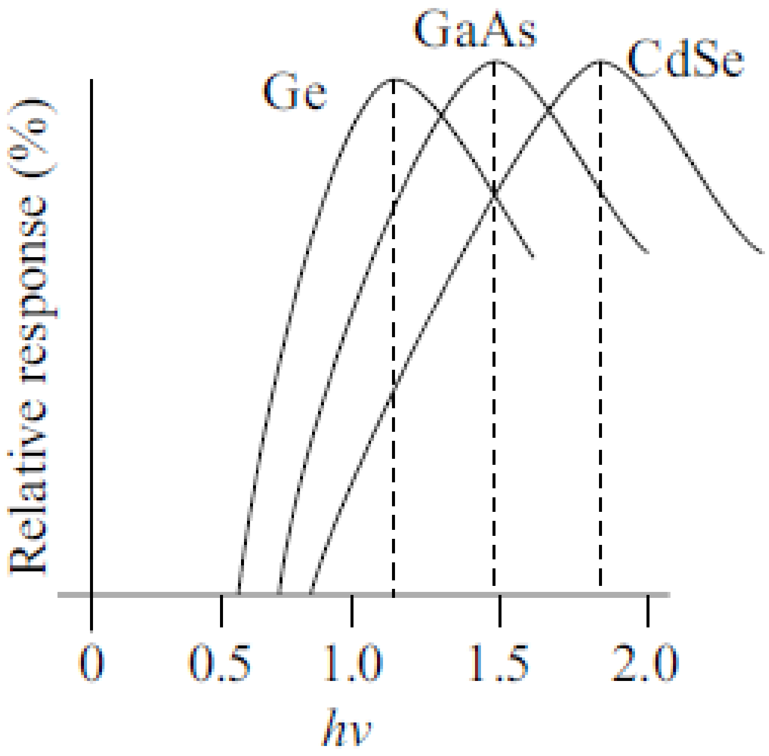


Fig. Spectral response for photoconducting materials

PHOTOCONDUCTOR

What are Characteristic Parameters ?

(3) Speed of photoresponsivity

- ✓ It is the rate of the change in photoconductivity with change in photo excitation intensity.
- ✓ For materials with exponential decay, the photocurrent reaches the dark current very quickly.
- ✓ For materials with non exponential decay ,the decay of photocurrent takes a longer time to reach dark current.

PHOTOCONDUCTOR

Photoconductive Materials

The desired characteristics are

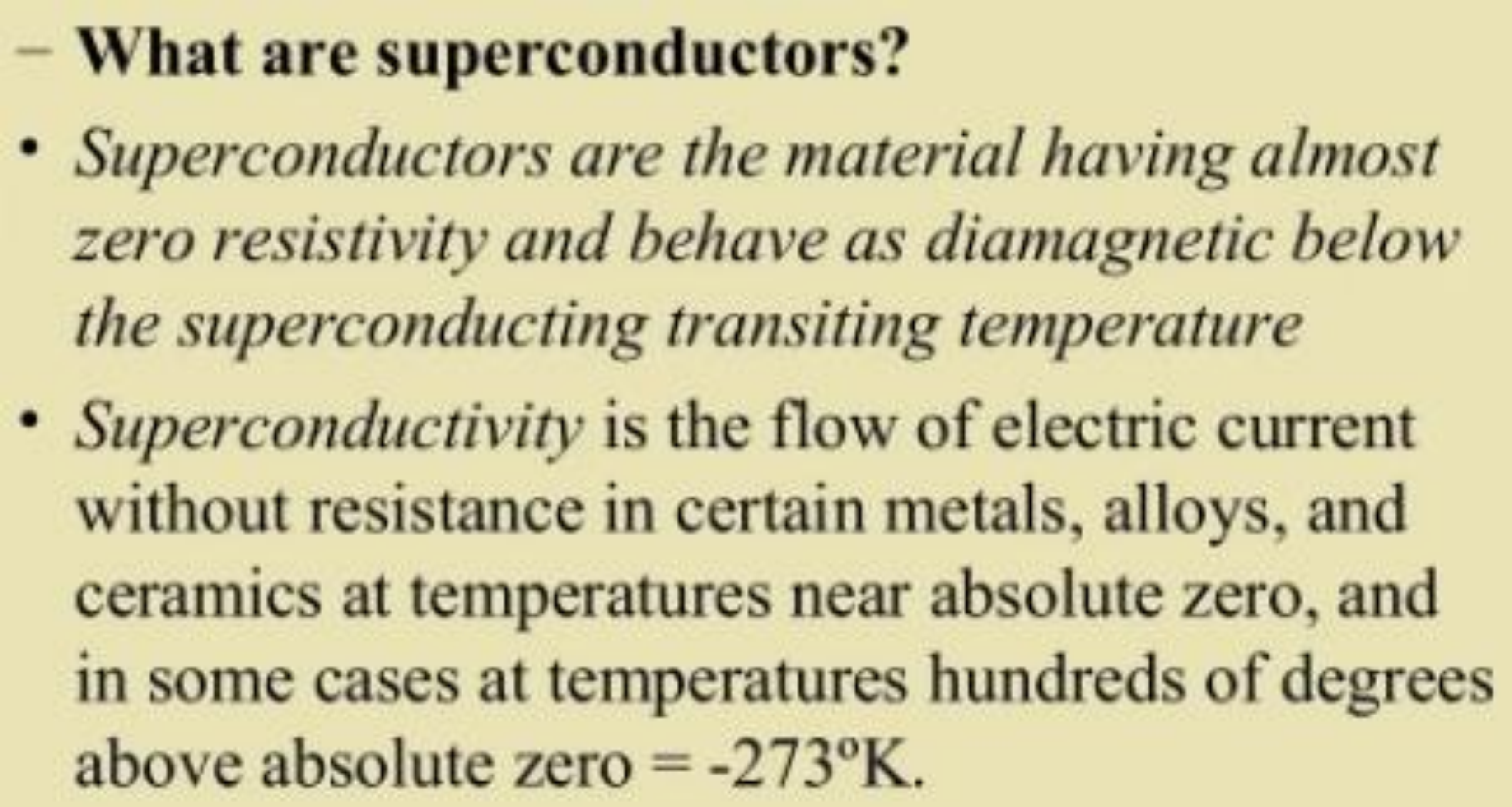
- ✓ High spectral sensitivity in the wavelength region of interest
- ✓ Higher quantum efficiency
- ✓ Higher photoconductive gain
- ✓ Higher speed of response and
- ✓ lesser noise

PHOTOCONDUCTOR

Photoconductive Materials

Material	Symbol	Detection Range (μm)
Lead sulphide	Pbs	0.6-3.0
Indium Antimony	InSb	1.0-7.0
Mercury-doped Germanium	Ge:Hg	2.0-13
Cadmium mercury telluride	CdHgTe	3.0-15
Copper-doped germanium	Ge:Cu	2.0-2.5
Cadmium sulphide	CdS	0.4-0.8
Cadmium selenide	CdSe	0.5-0.9

SUPERCONDUCTOR

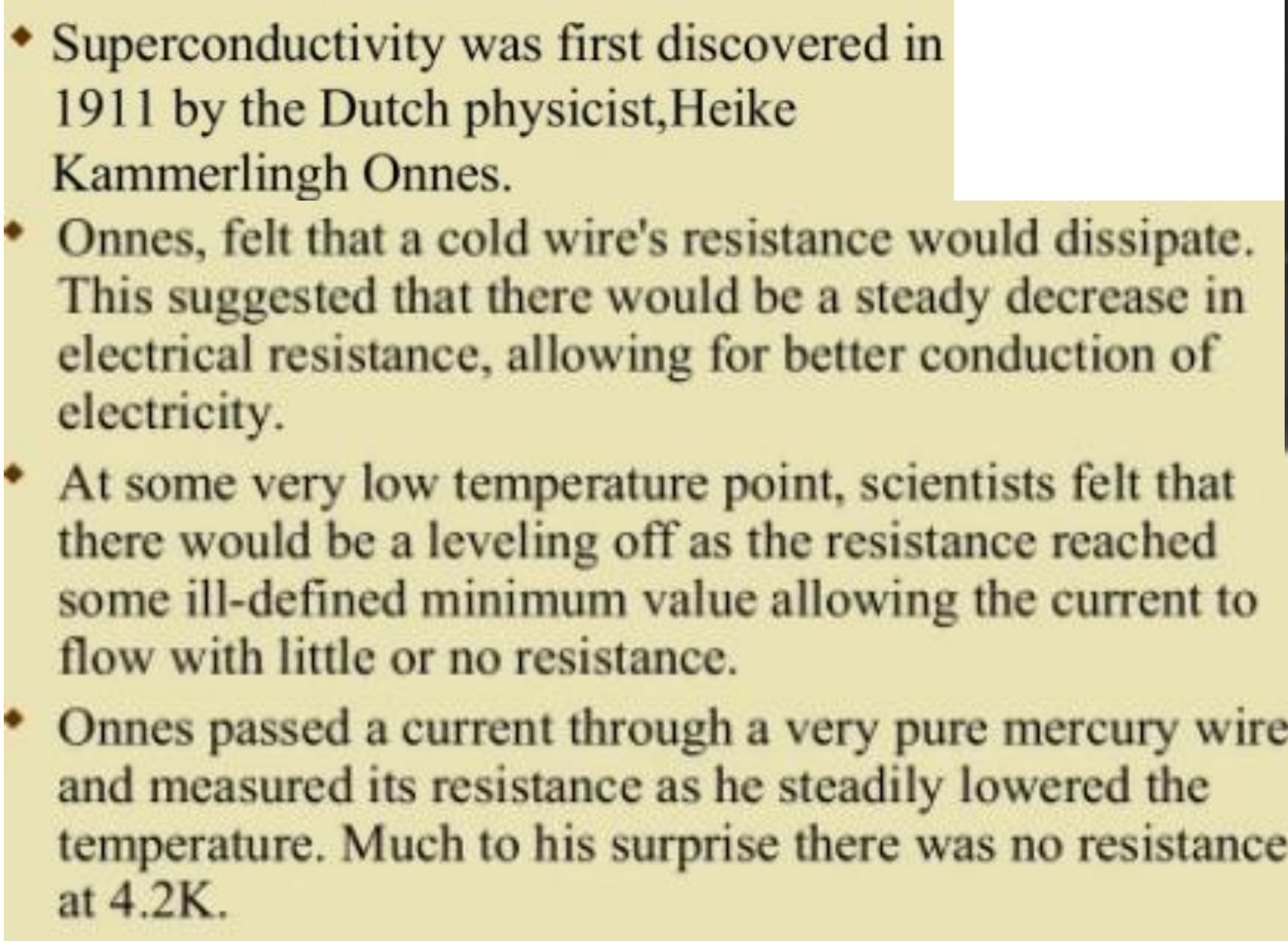


- **What are superconductors?**

- *Superconductors are the material having almost zero resistivity and behave as diamagnetic below the superconducting transiting temperature*
- *Superconductivity* is the flow of electric current without resistance in certain metals, alloys, and ceramics at temperatures near absolute zero, and in some cases at temperatures hundreds of degrees above absolute zero = -273°K.

SUPERCONDUCTOR

Discovery of superconductivity



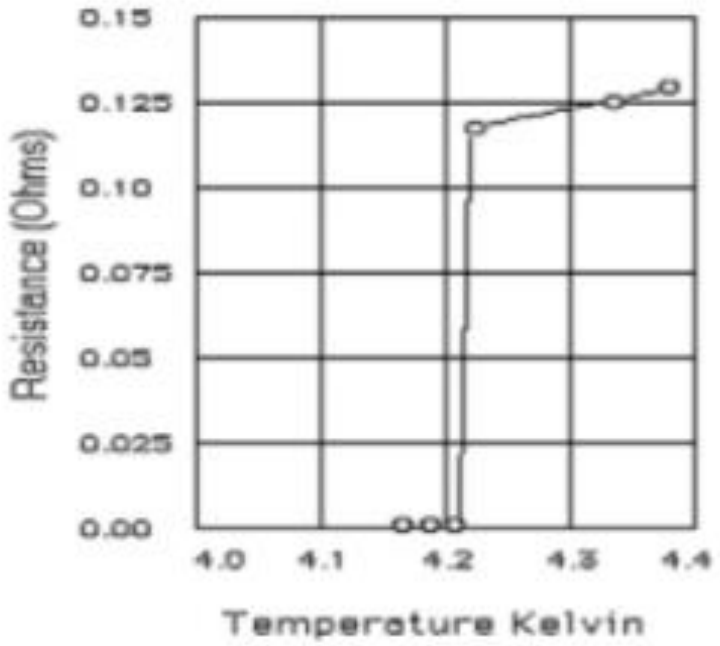
- Superconductivity was first discovered in 1911 by the Dutch physicist,Heike Kammerlingh Onnes.
- Onnes, felt that a cold wire's resistance would dissipate. This suggested that there would be a steady decrease in electrical resistance, allowing for better conduction of electricity.
- At some very low temperature point, scientists felt that there would be a leveling off as the resistance reached some ill-defined minimum value allowing the current to flow with little or no resistance.
- Onnes passed a current through a very pure mercury wire and measured its resistance as he steadily lowered the temperature. Much to his surprise there was no resistance at 4.2K.

SUPERCONDUCTOR

Discovery of superconductivity

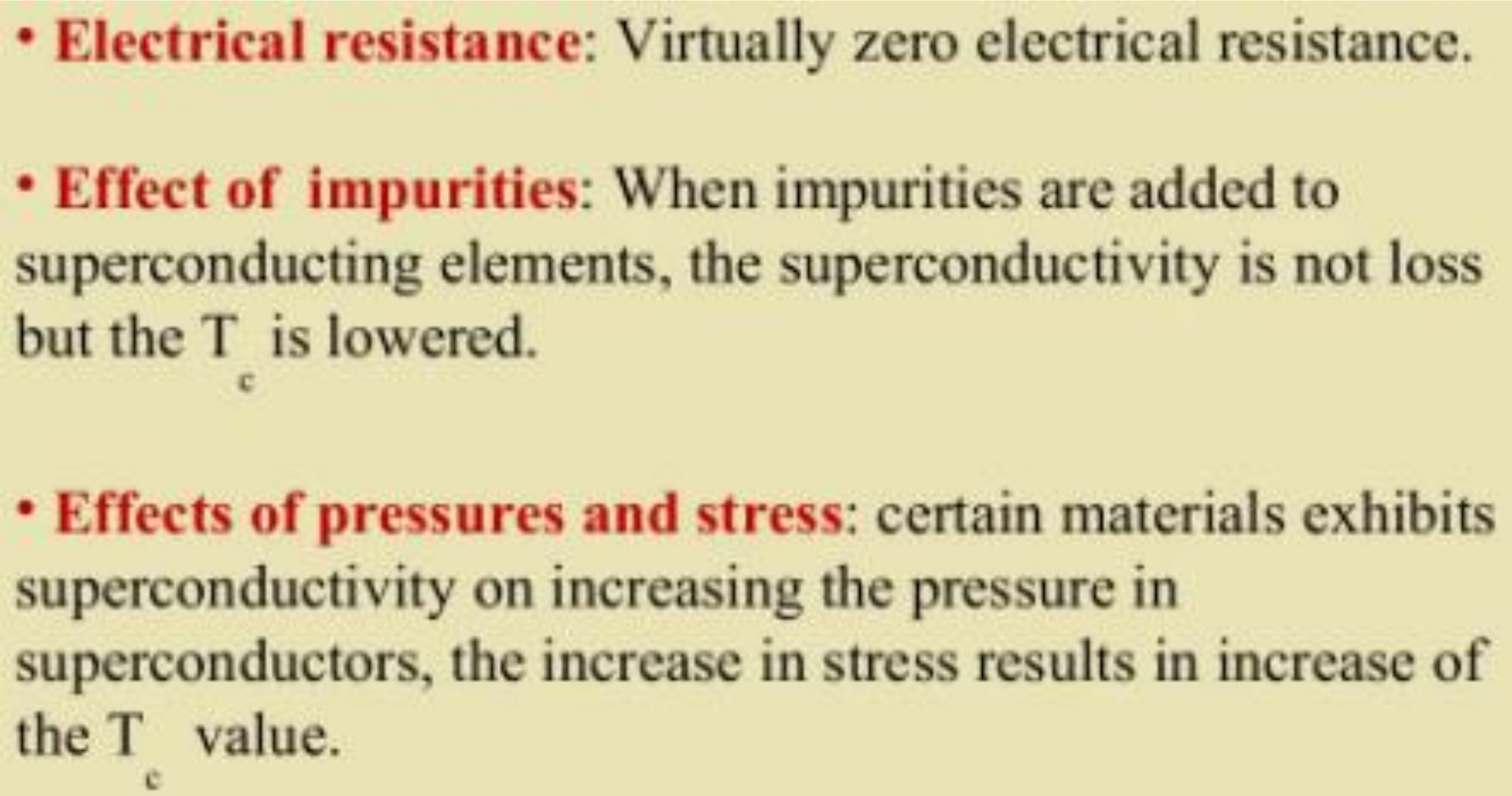
At 4.2K, the Electrical Resistance (opposition of a material to the flow of electrical current through it)Vanished, Meaning Extremely Good Conduction of Electricity-Superconductivity

Fig. 1



SUPERCONDUCTOR

Properties of superconductivity



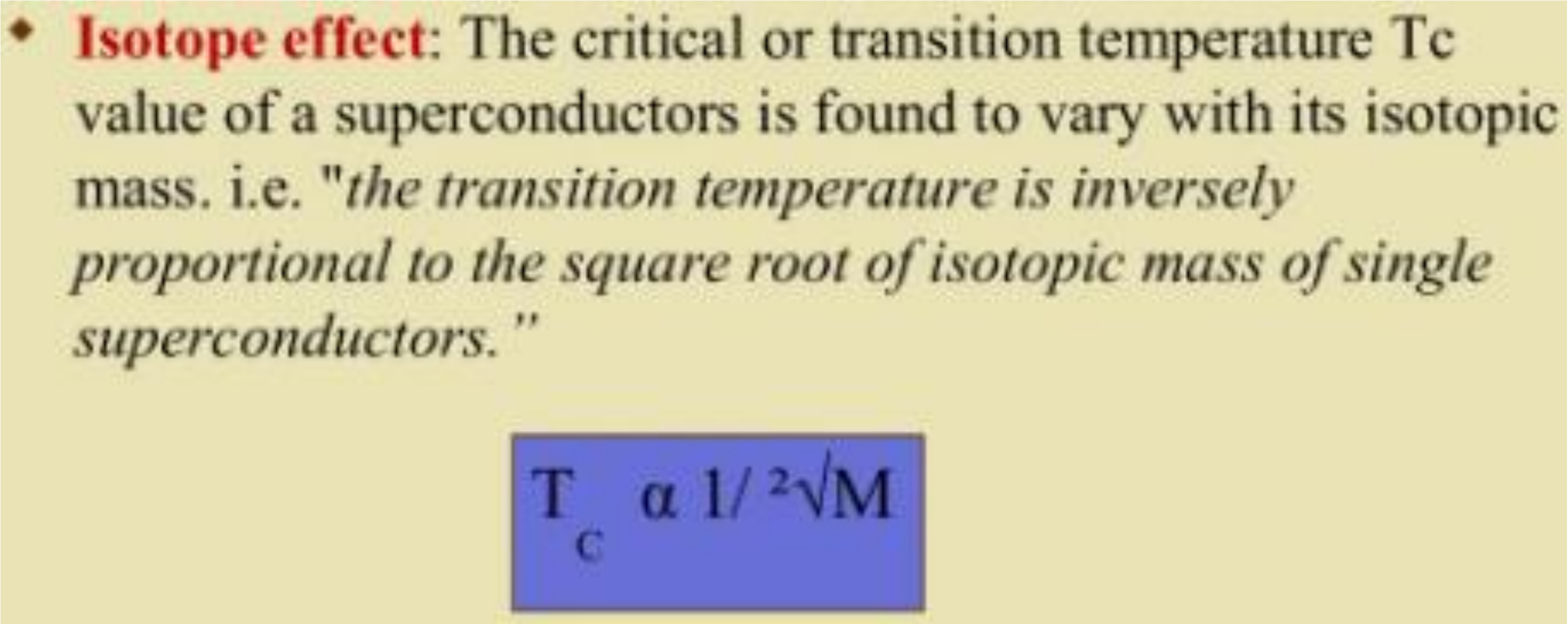
- **Electrical resistance**: Virtually zero electrical resistance.

- **Effect of impurities**: When impurities are added to superconducting elements, the superconductivity is not loss but the T_c is lowered.

- **Effects of pressures and stress**: certain materials exhibits superconductivity on increasing the pressure in superconductors, the increase in stress results in increase of the T_c value.

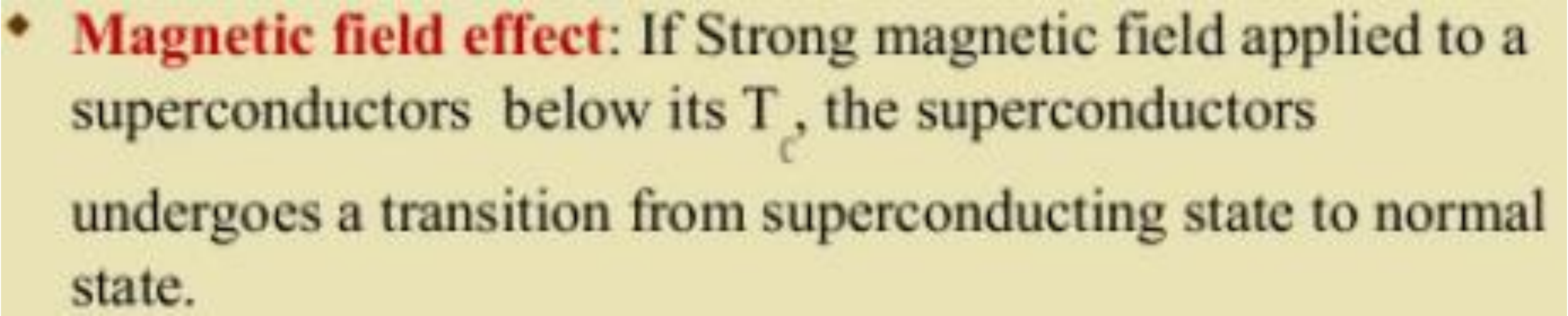
SUPERCONDUCTOR

Properties of superconductivity



- **Isotope effect**: The critical or transition temperature Tc value of a superconductors is found to vary with its isotopic mass. i.e. "*the transition temperature is inversely proportional to the square root of isotopic mass of single superconductors.*"

$$\boxed{T_C \;\alpha\; 1/\sqrt[2]{M}}$$



- **Magnetic field effect**: If Strong magnetic field applied to a superconductors below its T_c, the superconductors undergoes a transition from superconducting state to normal state.

SUPERCONDUCTOR

Properties of superconductivity

The superconducting state of the material cannot exist in presence of a magnetic field of critical value even at absolute zero temperature.

- Critical magnetic field (H_C) – Minimum magnetic field required to destroy the superconducting property at any temperature

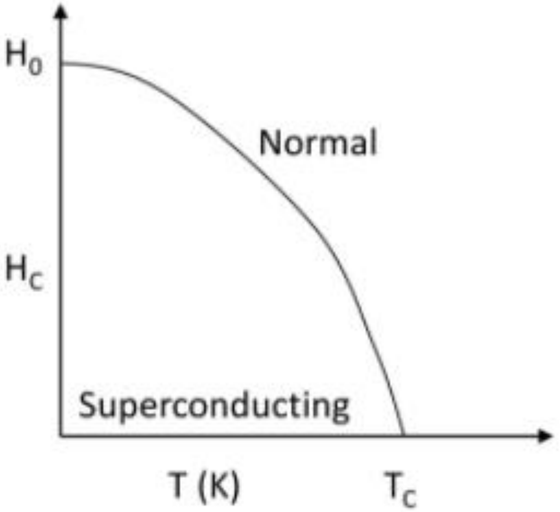
Element	H_C at 0K (mT)
Nb	198
Pb	80.3
Sn	30.9

$$H_C = H_0\left[1-\left(\frac{T}{T_C}\right)^2\right]$$

H_0 – Critical field at 0K

T - Temperature below T_C

T_C - Transition Temperature



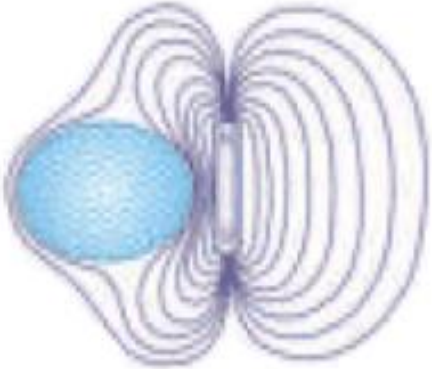
SUPERCONDUCTOR

Properties of superconductivity

Meissner effect: The complete expulsion of magnetic field by a superconducting material is called Meissner effect.

- When the superconducting material is placed in a magnetic field under the condition when $T \leq T_C$ and $H \leq H_C$, the flux lines are excluded from the material.

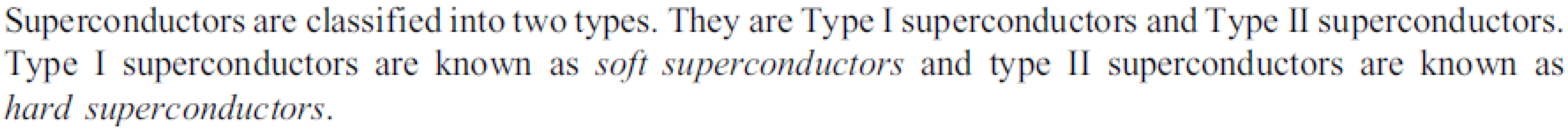
- Material exhibits perfect diamagnetism or flux exclusion.
- Deciding property
- $\chi = I/H = -1$
- Reversible (flux lines penetrate when T ↑ from T_C)



- Conditions for a material to be a superconductor
  - i. Resistivity $\rho = 0$
  - ii. Magnetic Induction $B = 0$ when in an uniform magnetic field
- Simultaneous existence of conditions

SUPERCONDUCTOR

Classification of superconductivity



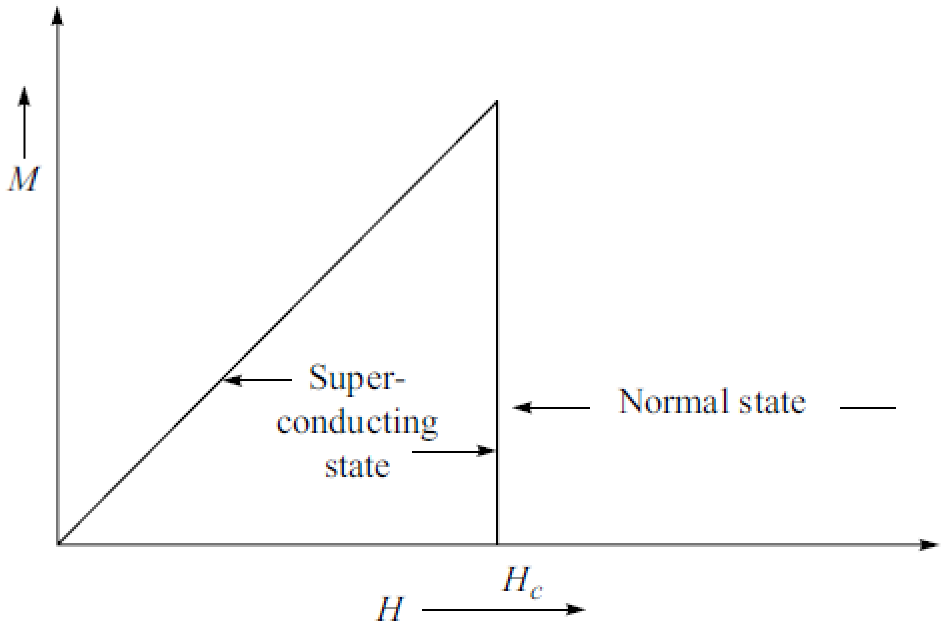
Superconductors are classified into two types. They are Type I superconductors and Type II superconductors. Type I superconductors are known as *soft superconductors* and type II superconductors are known as *hard superconductors*.

SUPERCONDUCTOR

Classification of superconductivity

Type I superconductors behave as perfect diamagnetic materials and obey the Meissner effect. Figure 20.5 shows the relation between the magnetisation produced and the applied magnetic field for Type I superconductors.

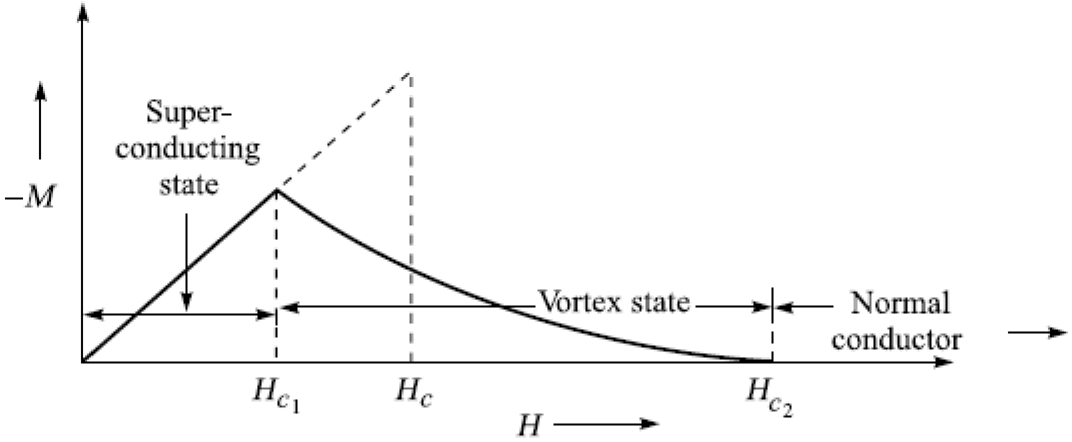
A negative sign is introduced in the magnetisation value to represent the diamagnetic property of the superconductor. The material produces a repulsive force up to the critical field H_c. Therefore, due to the repulsive force, it does not allow the magnetic field to penetrate through it. Hence, the material behaves as a superconductor. At H_c, the repulsive force is zero and hence, the material behaves as a normal conductor. Sn, Hg, Nb, V, $C_{0.1}$ $T_{0.3}$ $V_{0.6}$ are some examples of Type I superconductors.



SUPERCONDUCTOR

Classification of superconductivity

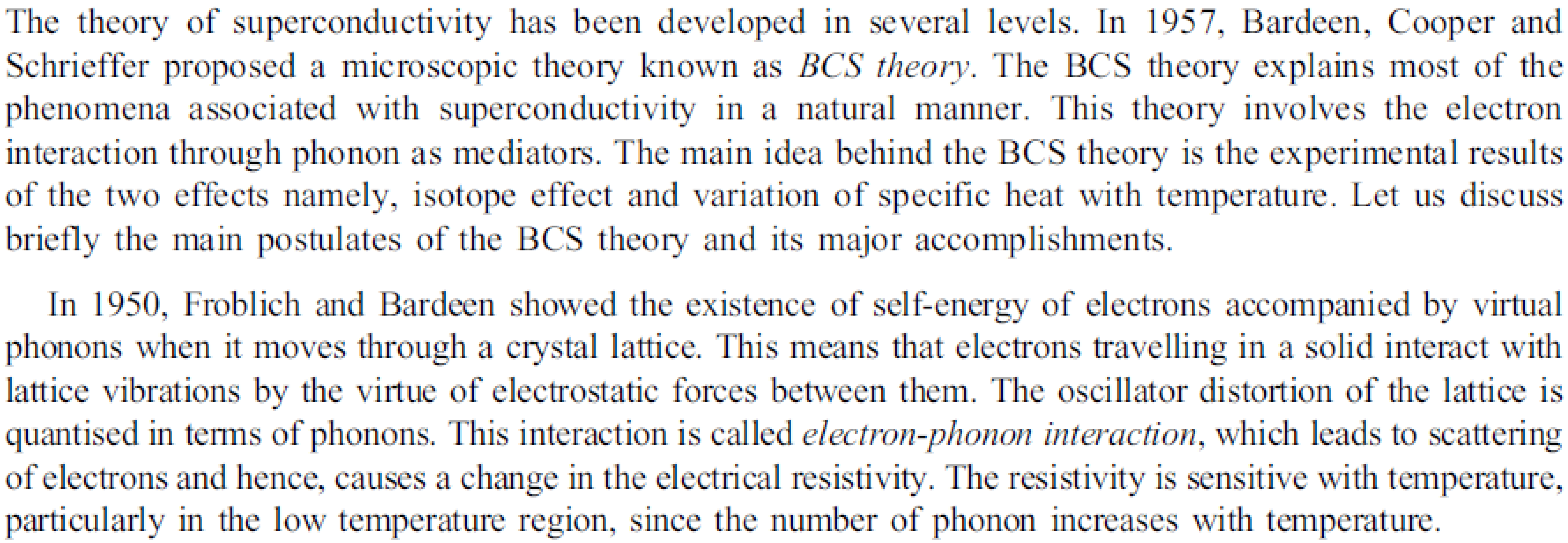
Type II superconductors do not perfectly obey the Meissner effect. These materials behave as a perfect superconductor up to H_{c1}. Above H_{c1}, the repulsive force decreases, resulting in decrease in the magnetisation M and hence, the magnetic flux starts to penetrate through the material. The magnetic field penetrates up to the value H_{c2}. In the region up to H_{c2}, the material behaves as a superconductor as shown in Fig. 20.6.



Let H_{c1} and H_{c2} be the lower and upper critical fields. The region between H_{c1} and H_{c2} is known as *vortex state* or *mixed state*. Above H_{c2}, the materials behave as normal conductors. Examples for type II superconductors are Nb_3 Sn, Nb_3 Ge, YBa_2 Cu_3 O_7.

SUPERCONDUCTOR

BARDEEN, COOPER AND SCHRIEFFER (BCS) THEORY of superconductivity



The theory of superconductivity has been developed in several levels. In 1957, Bardeen, Cooper and Schrieffer proposed a microscopic theory known as *BCS theory*. The BCS theory explains most of the phenomena associated with superconductivity in a natural manner. This theory involves the electron interaction through phonon as mediators. The main idea behind the BCS theory is the experimental results of the two effects namely, isotope effect and variation of specific heat with temperature. Let us discuss briefly the main postulates of the BCS theory and its major accomplishments.

In 1950, Froblich and Bardeen showed the existence of self-energy of electrons accompanied by virtual phonons when it moves through a crystal lattice. This means that electrons travelling in a solid interact with lattice vibrations by the virtue of electrostatic forces between them. The oscillator distortion of the lattice is quantised in terms of phonons. This interaction is called *electron-phonon interaction*, which leads to scattering of electrons and hence, causes a change in the electrical resistivity. The resistivity is sensitive with temperature, particularly in the low temperature region, since the number of phonon increases with temperature.

SUPERCONDUCTOR

BARDEEN, COOPER AND SCHRIEFFER (BCS) THEORY of superconductivity

It is assumed from the BCS theory that the electron-phonon interaction produces an attractive interaction between the two electrons. For example, an electron of wave vector K emits a virtual phonon, which is absorbed by an electron K^1. Thus, K is scattered as K–q and K^1+q, as shown in Fig. 20.7. The resulting electron–electron interaction depends on the relative magnitude of the electronic energy change and phonon energy. Once the phonon energy exceeds the electronic energy, the interaction becomes *attractive interaction* (Vph). Thus, for attractive interaction, the wave vector and spin are represented as $K\uparrow$and $K\downarrow$. Therefore, the two electrons interacting attractively in the phonon field are called *Cooper pair* and the same is shown in Fig. 20.7.

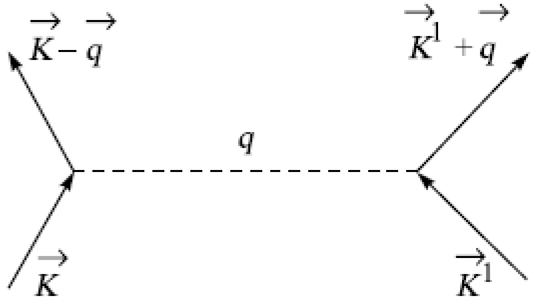


Fig. 20.7 *Electron–phonon interaction*

MAGNETIC PROPERTIES

Classification of magnetic materials:

- By the application of magnetic field some materials will not show any effect that are called non magnetic materials and those which show some effects are called magnetic materials.
- All magnetic materials magnetized in the presence of external magnetic field.
- Depending on the direction and magnitude of magnetization and also the effect of temperature on magnetic properties, all magnetic materials are classified into Dia, Para and Ferro magnetic materials.
- Two more classes of materials have structure very close to Ferro magnetic materials, but shows quiet different magnetic properties. They are Anti-Ferro magnetic and Ferri magnetic materials.

Diamagnetism:

- The number of orientations of electronic orbits in an atom be such that vector sum of magnetic moment is zero
- The external field will cause a rotation action on the individual electronic orbits this produces an induced magnetic moment which is in the direction opposite to the field and hence tends to decrease the magnetic induction present in the substance.
- Thus the diamagnetism is the phenomena by which the induced magnetic moment is always in the opposite direction of the applied field.

MAGNETIC PROPERTIES

Properties of diamagnetic materials:

- Diamagnetic material gets magnetized in a direction opposite to the magnetic field.
- Weak repulsion is the characteristic property of diamagnetism.
- Permanent dipoles are absent.
- Relative permeability is less than one but positive.
- The magnetic susceptibility is negative and small. It is not affected by temperature.
- Diamagnetism is universal i.e. all materials when exposed to external magnetic fields, tend to develop magnetic moments opposite in the direction to the applied field.
- When placed inside a magnetic field, magnetic lines of force are repelled.

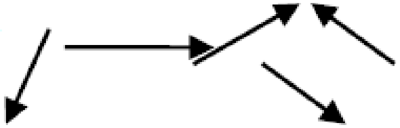
Para magnetism:

- The number of orientations of orbital and spin magnetic moments be such that the vector sum of magnetic moment is not zero and there is a resultant magnetic moment in each atom even in the absence of applied field.
- The net magnetic moments of the atoms are arranged in random directions because of thermal fluctuations, in the absence of external magnetic field. Hence there is no magnetization.
- If we apply the external magnetic field there is an enormous magnetic moment along the field direction and the magnetic induction will be increase. Thus induced magnetism is the source of par magnetism.

MAGNETIC PROPERTIES

Properties of paramagnetic materials:

- Paramagnetic materials get magnetized in the direction of the magnetic field.
- Weak attraction is characteristic property of Para magnetism.
- Paramagnetic material has magnetic dipoles.
- Relative permeability is greater than one but small i.e. this indicate that when paramagnetic substance is placed in a uniform magnetic field, the field inside the material will be more than the applied field.
- The magnetic susceptibility is small and positive. The magnetic susceptibility of paramagnetic is inversely proportional to absolute temperature i.e. $\chi = C/T$. This is called curie law, c is called Curie constant.
- Paramagnetic susceptibility is independent of the applied field strength.
- Spin alignment is random



- When placed inside a magnetic field it attracts the magnetic lines of force.
- Examples: Aluminum, Manganese, oxygen.

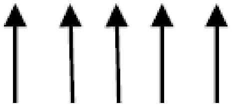
MAGNETIC PROPERTIES

Ferromagnetism:

- Ferromagnetism arises when the magnetic moments of adjacent atoms are arranged in a regular order i.e all pointing in the same direction.
- The ferromagnetic substances posses a magnetic moment even in the absence of the applied magnetic field, this magnetization is known as the spontaneous magnetization.
- There is a special form of interaction called “exchange “coupling occurring between adjacent atoms, coupling their magnetic moment together in rigid parallelism.

Properties of ferromagnetic materials:

- In ferromagnetic materials, large magnetization occurs in the direction of the field.
- Strong attraction is the characteristic property of ferromagnetism.
- They exhibit spontaneous magnetization.
- The relative permeability is very high for Ferro magnetic.
- The magnetic susceptibility is positive and very high.
- Magnetic susceptibility is fairly high and constant up to a certain temperature according the equation $\chi = \frac{C}{T-T_C}$ C= curie constant T_c = Curie temperature.
- Ferromagnetism is due to the existence of magnetic domains which can be spontaneously magnetized.
- Exhibit hysteresis phenomenon.
- Spin alignment is parallel in the same direction



- When placed inside a magnetic field they attract the magnetic lines of forces very strongly.
- Examples: Iron, Nickel, Cobalt.

MAGNETIC PROPERTIES

Domain theory of ferromagnetism:

- According to Weiss, the specimen of ferromagnetic material having number regions or domains which are spontaneously magnetized. In each domain spontaneous magnetization is due to parallel alignment of all magnetic dipoles.
- The direction of spontaneous magnetization varies from domain to domain.
- The resultant magnetization may hence be zero or nearly zero.
- When an external field is applied there are two possible ways for the alignment of domains.

(i)**By motion of domain walls:** The volume of domains that are favorably oriented with respect to the magnetizing field increases at the cost of those that are unfavorably oriented. [Fig (b)]

(ii)**By rotation of domains**: when the applied magnetic field is strong, rotation of the direction of magnetization occurs in the direction of the field. [Fig(c)]

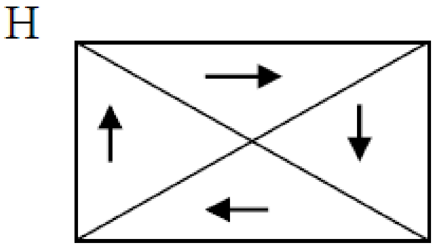


Fig (a)

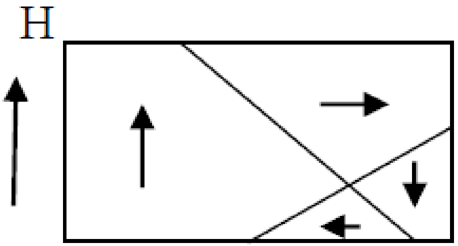
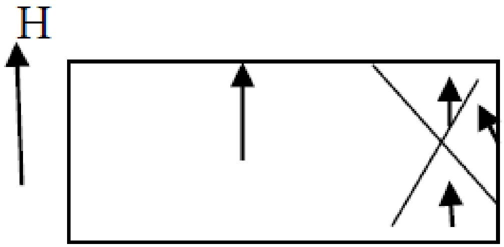


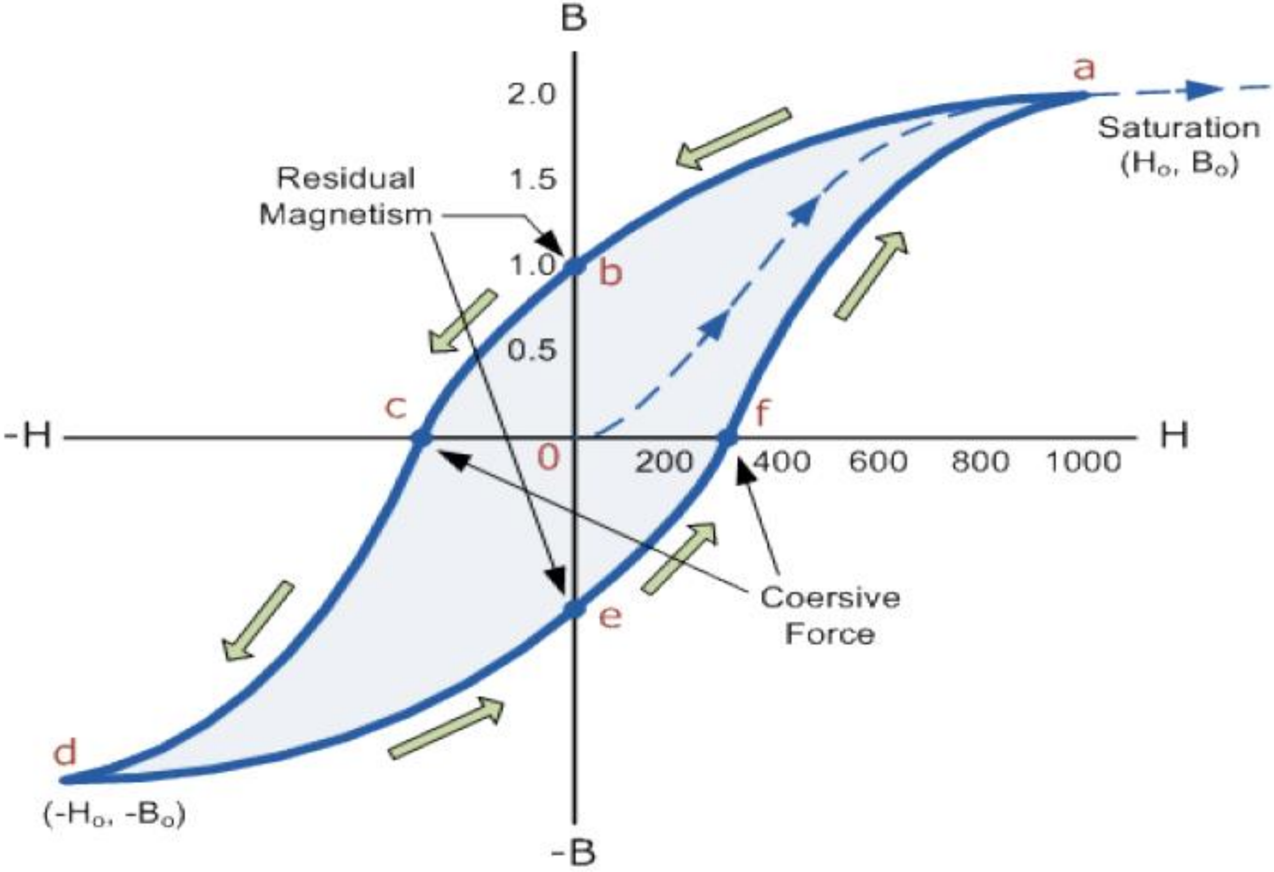
fig (b)



fig(c)

MAGNETIC PROPERTIES

Hysteresis curves

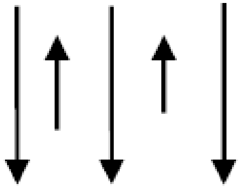


MAGNETIC PROPERTIES

- **Hysteresis**: Lagging of magnetization behind the magnetizing field (H).
- When a Ferro magnetic material is subjected to external field, there is an increase in the value of the resultant magnetic moment due to two processes.
- The movement of domain walls
- Rotation of domain walls
- When a weak magnetic field is applied, the domains are aligned parallel to the field and magnetization grows at the expense of the less favorably oriented domains.
- This results in the Bloch wall (or) domain wall movement and the weak field is removed the domains reverse back to their original state. This reversible wall displacement is indicated by OA the magnetization curve.
- When the field becomes stronger than the domain wall movement, it is mostly reversible movement. This is indicated by path AB of the graph. The phenomenon of hysteresis is due to the irreversibility.
- At the point B all domains have got magnetized, application of higher field rotates the domains into the field direction indicated by BC. Once the domains rotation is complete the specimen is saturated denoted by C.
- Thus the specimen is said to be attain the maximum magnetization. At this position if the external field is removed (H=0), the magnetic induction B will not fall rapidly to zero ,but falls to D rather than O. This shows that even when the applied field is zero the material still have some magnetic induction (OD) which is called residual magnetism or retentivity.

MAGNETIC PROPERTIES

- Actually after the removal of the external field the specimen will try to attain the original configuration by the movement of domain walls. But this movement is stopped due to the presence of impurities, lattice imperfections.
- Therefore to overcome this, large amount of reverse magnetic field (H_c) is applied to the specimen .The amount of energy spent to reduce the magnetization (B) to zero is called “coercivity” represented by OE in the fig.
- **HSTERESIS:** lagging of magnetization (B) behind the magnetizing field (H) is called hysteresis.
- **Hysteresis loss:** It is the loss of energy in taking a ferromagnetic body through a complete cycle of magnetization and this loss is represented by the area enclosed by the hysteresis loop.
- Ferri magnetic substances are the materials in which the atomic or ionic dipoles in one direction are having unequal magnitudes. This alignment of dipole gives a net magnetization and those magnetic substances which have two or more different kind of atoms. These are also called Ferrites.



MAGNETIC PROPERTIES

- In Ferri magnetic materials there, they may have large net magnetization as compared to anti Ferro magnetic materials.
- Ferrimagnetic materials generally known as ferrites consist of two or more different kind of atoms their formula is $M_e^{++}Fe_2^{++}O_4^{--}$.
- Where M_e^{++} stands for a suitable divalent metal ion such as Fe^{++}, CO^{++}, Ni^{++}, Mg^{++}, etc, Fe_2^{++} is a trivalent ferric ion.

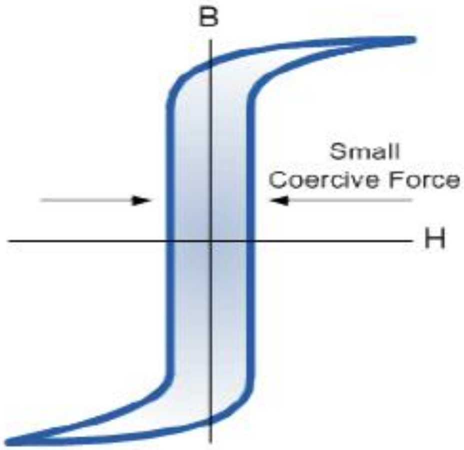
Applications of ferrites:

- They are used to produce ultrasonics by magnetization principle.
- Ferrites are used in audio and video transformers.
- Ferrites rods are used in radio receivers to increase the sensitivity.
- They are also used for power limiting and harmonic generation.
- Ferrites are used in computers and data processing circuits.
- Ferrites are used in switching circuits and in storage devices of computers.
- Ferrites are not metals but their resistivity lies in the range of insulators or semiconductors.

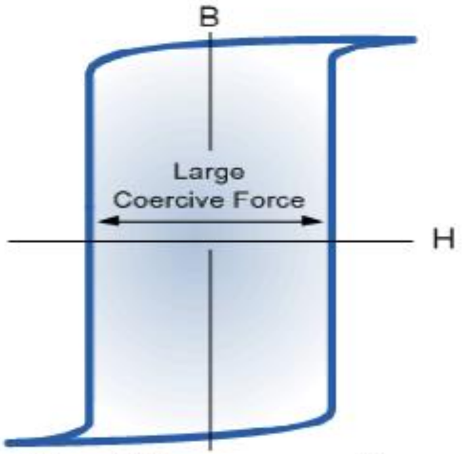
MAGNETIC PROPERTIES

Hard and soft magnetic materials:

- The process of magnetization of a Ferro or Ferri magnetic material consist of moving domains walls so that favorably oriented domains grow and shrink. If the domain walls are easy to move and coercive field is low and the material is easy to magnetize. Such a material is called soft magnetic material.
- If it is difficult to move the domain walls, the coercive field is large then the material is magnetically hard .These are called hard magnetic material.



"Soft" Ferromagnetic
Material



"Hard" Ferromagnetic
Material

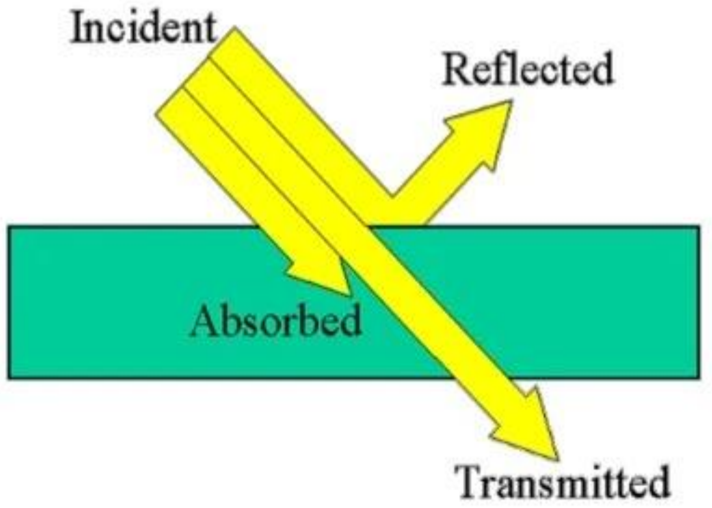
MAGNETIC PROPERTIES

Hard magnetic materials	Soft magnetic materials
(i)Hard magnetic materials have large hysteresis loss due to large hysteresis is loop area.	(i)Soft magnetic materials have low hysteresis Loss due to small hysteresis loop area.
(ii)In these materials the domain wall movement is difficult because of presence of impurities and crystal imperfection and it is irreversible in nature.	(ii)In these materials the domain wall movement is relatively easier, even for small changes in the magnetizing field the magnetization changes by large amount.
(iii) The coercivity and retentivity are large. Hence these materials cannot be easily magnetised and demagnetized	(iii)The coercivity and retentivity are small .Hence these materials can be easily magnetized and demagnetized.
(iv) In these materials, because of the presence of impurities and crystal imperfection the mechanical strain is more. Hence magneto static energy is large.	(iv)These materials are free from irregularities; the magneto static energy is small.
(v)These materials have small values of susceptibility and permeability.	(v)These materials have large values of susceptibility and permeability.

MAGNETIC PROPERTIES

Hard magnetic materials	Soft magnetic materials
(vi)These are used to make permanent magnets. Example 1. copper nickel iron alloy 2. copper nickel cobalt alloy 3.iron-nickel-aluminum alloys with certain amount of cobalt called alnico alloy	(vi)These are used to make electronic magnets. Example 1. iron silicon alloys 2. ferrites 3.garnets
(vii) Applications: For production of permanent magnets used in magnetic detectors, microphones flux meters, voltage regulators, damping devices, magnetic separators, and loud speakers.	(Vii)Applications: Mainly used in electromagnetic machinery and transformer cores. They are used in switching circuits, microwave insulators and matrix storage of computers.

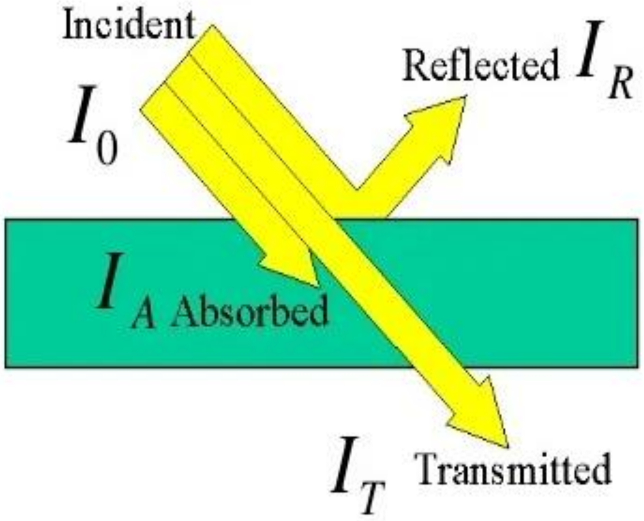
OPTICAL PROPERTIES



- Consider EM Radiation with Intensity I_0 (in W/m^2) Impinging on a Solid
- The EM-Solid interaction Alters the incident Beam by 3 possible Phenomena
  - The EM Beam can be
    - Reflected
    - Absorbed
    - Transmitted

- An Energy Balance on the Solid:
  - E-in = E-reflected + E-absorbed + E-transmitted

$$I_0 = I_R + I_A + I_T$$



- Now Divide E-Balance equation by I_0

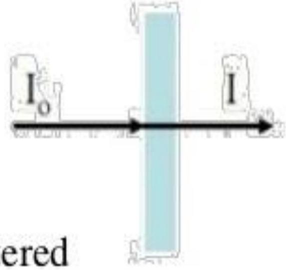
$$1 = R + A + T$$

- Where:
  - R ≡ REFLECTANCE (I_R/I_0)
  - A ≡ ABSORBANCE (I_A/I_0)
  - T ≡ TRANSMITTANCE (I_T/I_0)

Classification of Optical Materials

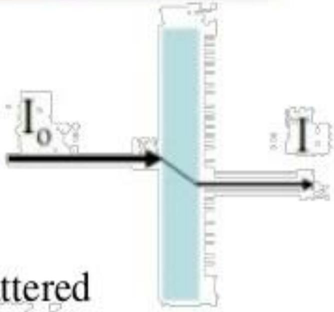
1.Transparent Materials

- Transparent →
  - T >> A+R
  - Light Not Scattered



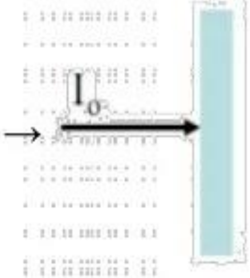
2.Translucent Materials

- Translucent→
  - T > A+R
  - Light Scattered



3.Opaque Materials

- Opaque →
  - T = 0

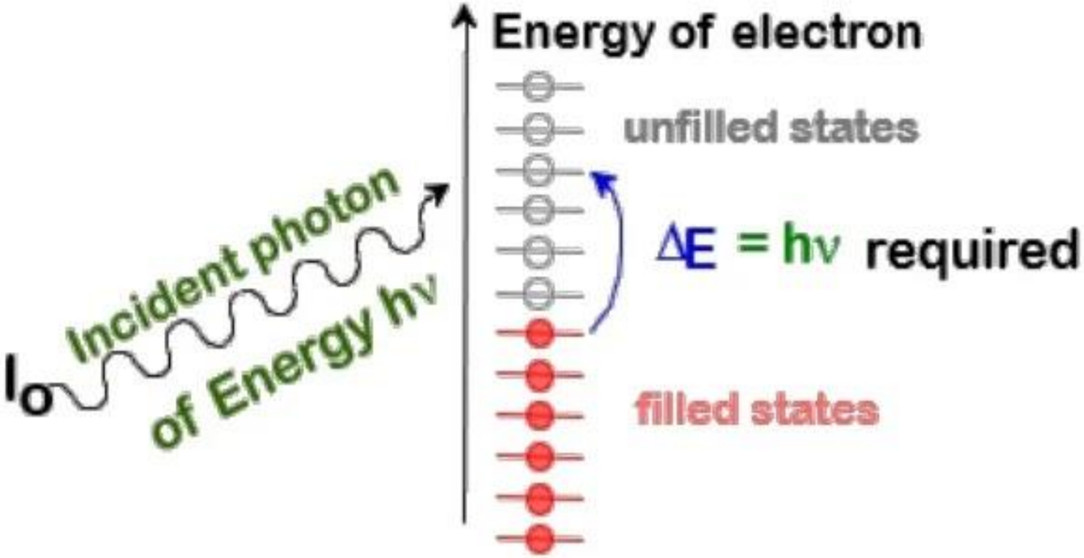


Metals – Optical Absorption

- Metals Interact with Light Thru QUANTIZED Photon Absorption by Electrons

- Metals have Very Closely Spaced e- Energy Levels

•Thus Almost ALL incident Photons are ABSORBED within about 100 nm of the surface

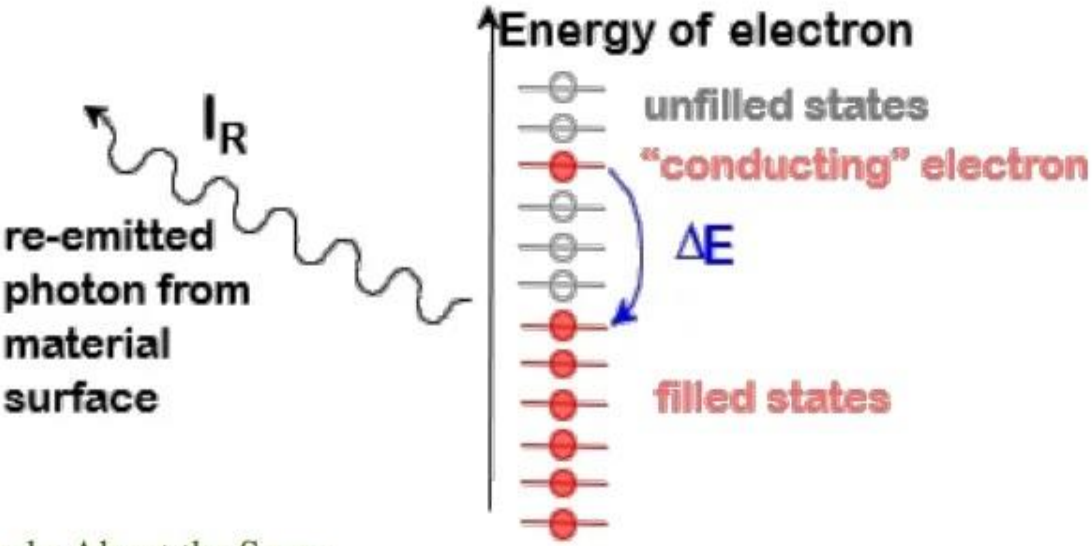


- Unfilled electron state are adjacent to filled states
- Near-surface electrons absorb visible light

Metals – Optical Reflection

- The Absorbed Energy is ReEmitted by e- “falling” back to Lower Energy states

- Since Metals have Very Closely Spaced e- Energy Levels The Light is emitted at many ν’s



- Thus Outgoing Light Looks About the Same as Incoming Light → High Reflectance

Optical Properties – Non-Metals

Reflection

- The reflectivity R represents the fraction of the incident light that is reflected at the interface,

$$R = \frac{I_R}{I_0}$$

- If the light is normal (or perpendicular) to the interface, then.

$$R = \left(\frac{n_2 - n_1}{n_2 + n_1}\right)^2$$

- When light is transmitted from a vacuum or air into a solid s, then

$$R = \left(\frac{n_s - 1}{n_s + 1}\right)^2$$

- Example: For Diamond $n = 2.41$

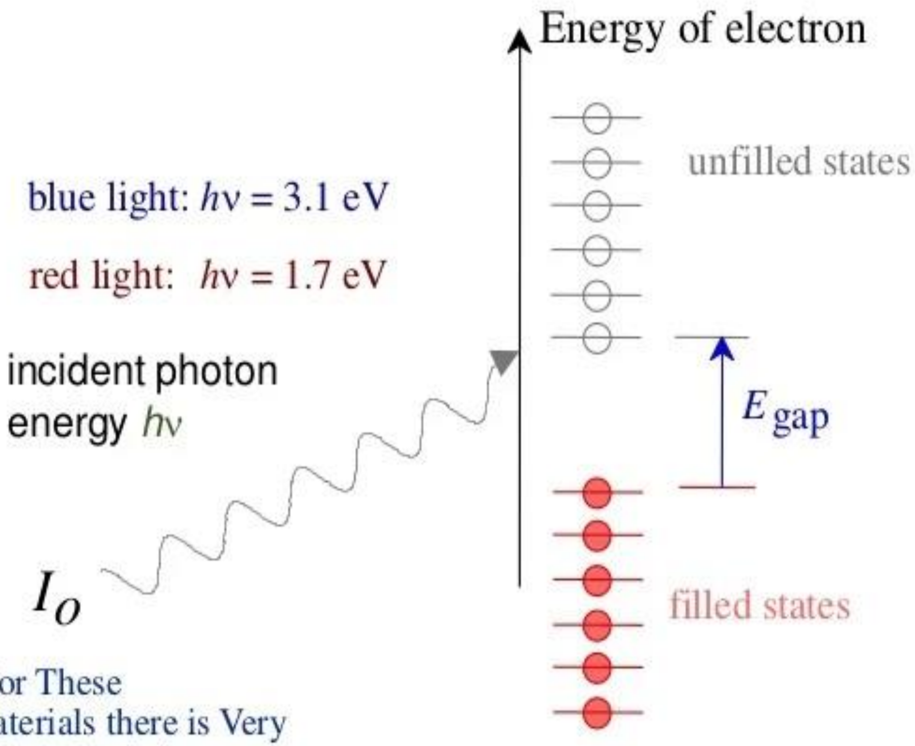
$$R = \left(\frac{2.41 - 1}{2.41 - 1}\right)^2 = 0.17$$

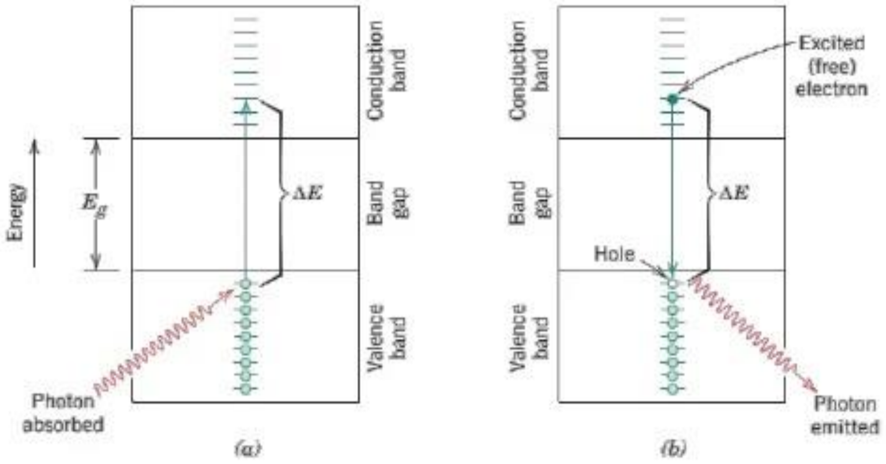
0.17% of light is reflected

- Reflection losses for lenses and other optical instruments are minimized significantly by coating the reflecting surface with very thin layers of dielectric materials such as magnesium fluoride (MgF2).

Absorption

- In The Case of Materials with "Forbidden" Gaps in the Band Structure, Absorption Occurs only if hν>E_{gap}





- For These Materials there is Very little ReEmission

- The Material Color Depends on the Width of the BandGap

Color Cases – BandGap Matls

- $E_{gap} < 1.8$ eV
  - ALL Visible Light Absorbed; Solid Appears

    Gray or Black in Color
    - e.g., Si with $E_{gap} = 1.1$ eV
- $E_{gap} > 3.1$ eV
  - NO Visible Light Absorbed; Solid Appears Clear and Transmissive
    - e.g., Diamond $E_{gap} = 5.45$ eV, SiO_2 $E_{gap} = 8\text{-}9$ eV
- $1.8 \text{ eV} < E_{gap} < 3.1$ eV
  - Some Light is absorbed and Material has a color

NonMetal Colors

- Color determined by the sum of frequencies
  - transmitted light
  - re-emitted light from electron transitions
- e.g., Cadmium Sulfide (CdS)
  - $E_{gap} = 2.4eV$
  - Absorbs higher energy visible light (blue, violet),

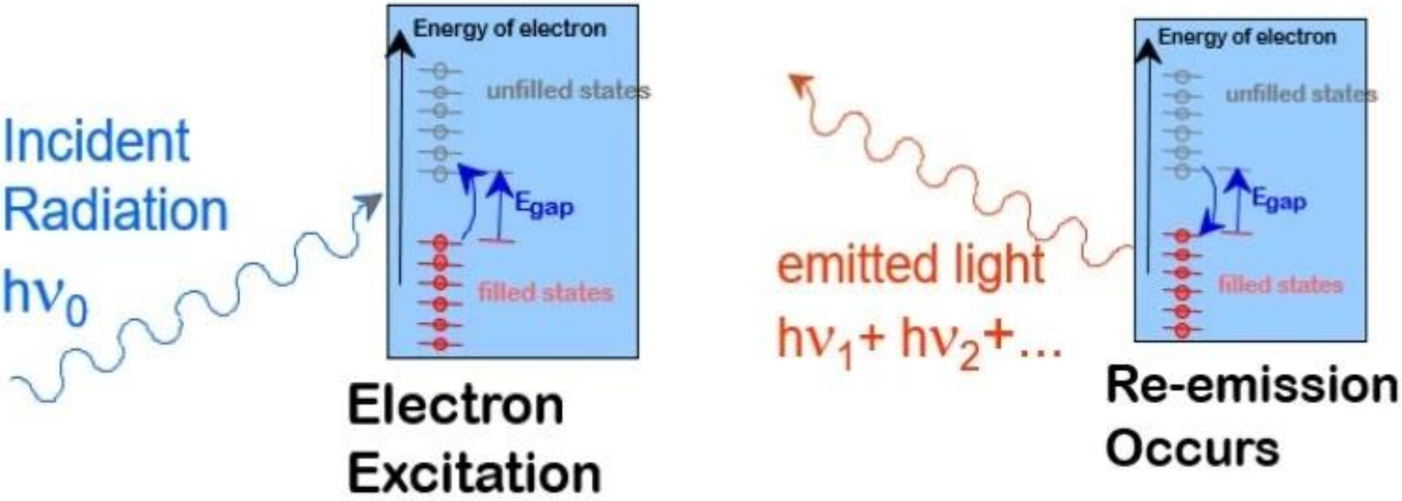
- Red/yellow/orange is transmitted and gives it this color

- CdS

Luminescence

- With luminescence, energy is absorbed as a consequence of electron excitations, which is subsequently reemitted as visible light. When light is reemitted in less than a second after excitation, the phenomenon is called fluorescence. For longer reemission times, the term phosphorescence is used.
- Electroluminescence is the phenomenon whereby light is emitted as a result of electron–hole recombination events that are induced in a forward-biased diode
- The device that experiences electroluminescence is the light-emitting diode (LED).

- Based on EM Induced e⁻ excitation, and then Relaxation with Broad-Spectrum hν Emission



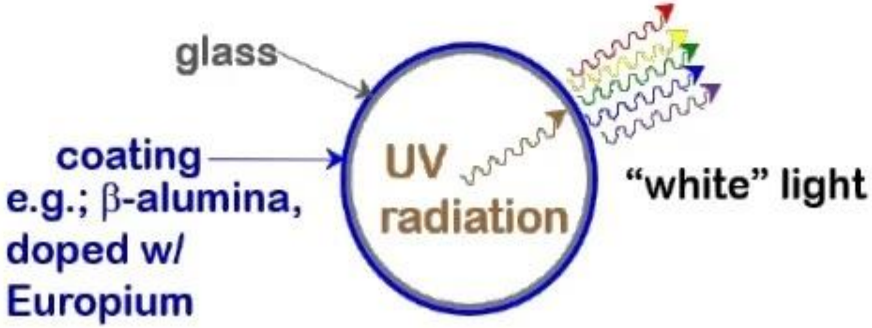
Incident Radiation $h\nu_0$

Electron Excitation

emitted light $h\nu_1 + h\nu_2 + \ldots$

Re-emission Occurs

- e.g. fluorescent lamps



coating e.g.; β-alumina, doped w/ Europium

UV radiation

"white" light

Summery

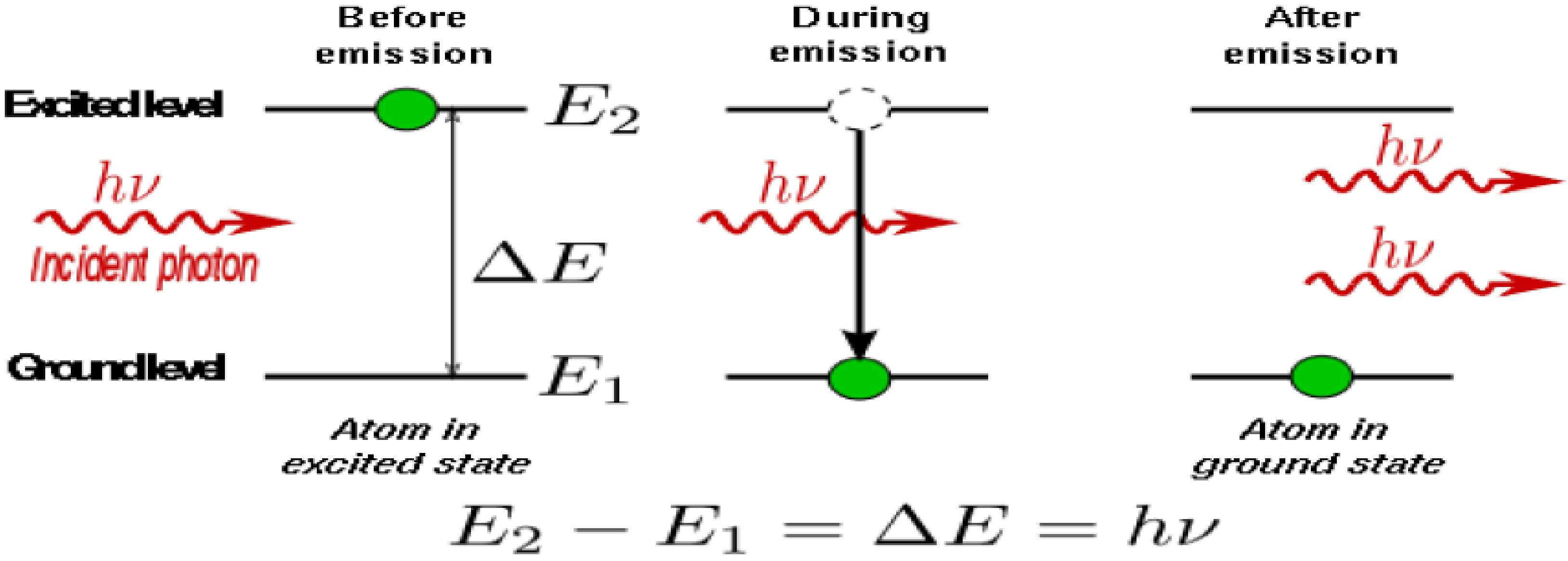
- When light (radiation) shines on a material, it may be:
  -- reflected, absorbed and/or transmitted.
- Optical classification:
  -- transparent, translucent, opaque
- Metals:
  -- fine succession of energy states causes absorption and reflection.
- Non-Metals:
  -- may have *full* ($E_{gap} < 1.8$eV) , *no* ($E_{gap} > 3.1$eV), or *partial* absorption ($1.8\text{eV} < E_{gap} = 3.1$eV).
  -- color is determined by light wavelengths that are transmitted or re-emitted from electron transitions.
  -- color may be changed by adding impurities which change the band gap magnitude (e.g., Ruby)
- Refraction:
  -- speed of transmitted light varies among materials.

LASER

- **Laser:** Laser means **Light Amplification by Stimulated Emission of Radiation.**
- **Absorption:** When at atom absorbs an amount of energy ‘hv’ in the form of photon from the external agency and excited into the higher energy levels from ground state, then this process is known as absorption. Atom + hv ➝ atom*
- **Spontaneous Emission:** When an atom in the excited state emits a photon of energy ‘hv’ coming down to ground state by itself without any external agency, such an emission is called spontaneous emission. Atom* ➝ atom + hv
- Photons released in spontaneous emission are not coherent. Hence spontaneous emission is not useful for producing lasers.
- **Stimulated Emission:** When an atom in the excited state, emits two photons of same energy ‘hv’ while coming to down to ground state with the influence of an external agency, such an emission is called stimulated emission. Atom* ➝ atom + 2hv
- In the two photons one photon induces the stimulated emission and the second one is released by the transition of atom from higher energy level to lower energy level.
- Both the photons are strictly coherent. Hence stimulated emission is responsible for laser production.

LASER

- **Laser Production Principle:**
- Two coherent photons produced in the stimulated emission, interacts with other two excited atoms, resulting in four coherent photons.
- Thus, coherent photons are multiplied in a lasing medium. The continuous successive emission of photons results for the production of laser beam.



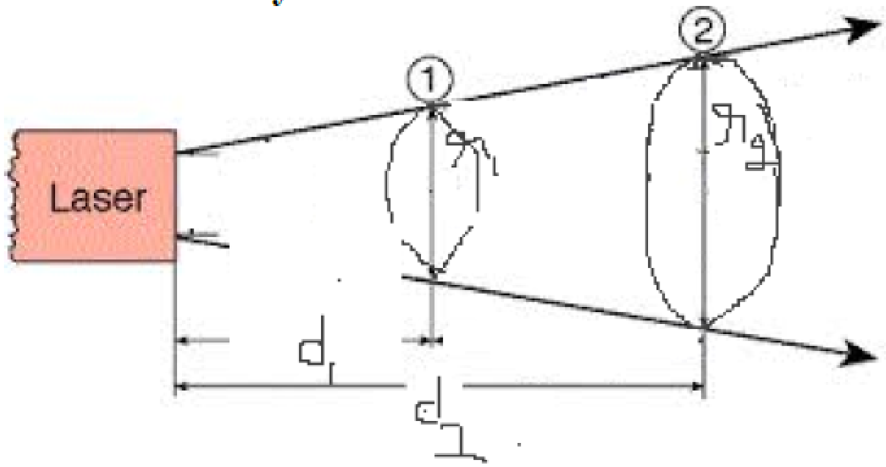
$$E_2 - E_1 = \Delta E = h\nu$$

LASER

Characteristics of Laser Beam: Some of the special properties which distinguish lasers from ordinary light sources are characterized by:

1. Directionality
2. High Intensity
3. Mono- chromacity
4. Coherence

1.Directionality:



Laser emits radiation only in one direction. The directionality of laser beam is expressed in terms of angle of divergence (Φ)

Divergence or Angular Spread is given by **$\Phi = r_2 - r_1 / d_2 - d_1$**

Where d_1, d_2 are any two distances from the laser source emitted and r_1, r_2 are the radii of beam spots at a distance d_1 and d_2 respectively as shown in above figure. Laser light having less divergence, it means that laser light having more directionality.

LASER

2. High Intensity: Generally, light from conventional source spread uniformly in all directions. For example, take 100 watt bulb and look at a distance of 30 cm, the power enter into the eye is less than thousand of a watt. This is due to uniform distribution of light in all directions.

But in case of lasers, light is a narrow beam and its energy is concentrated within the small region. The concentration of energy accounts for greater intensity of lasers.

3. Monochromacity: The light emitted by laser is highly monochromatic than any of the other conventional monochromatic light. A comparison b/w normal light and laser beam, ordinary sodium (Na) light emits radiation at wave length of $5893A^0$ with the line width of $1A^0$. But He-Ne laser of wave length $6328A^0$ with a narrow width of only 10^{-7} A^0 i.e., Monochromacity of laser is 10 million times better than normal light.

The degree of Monochromacity of the light is estimated by line of width (spreading frequency of line).

4. Coherence: If any wave appears as pure sine wave for longtime and infinite space, then it is said to be perfectly coherent.

Practically, no wave is perfectly coherent including lasers. But compared to other light sources, lasers have high degree of coherence because all the energy is concentrated within the small region. There are two independent concepts of coherence.

i) Temporal coherence (criteria of time)

ii) Spatial coherence (criteria of space)

LASER

Population Inversion:

- Generally, number of atoms in the ground state is greater than the number of atoms in higher energy states.
- But in order to produce a laser beam, the minimum requirement is stimulated emission.
- Stimulated emission takes place only if the number of atoms in the higher energy level is greater than the number of atoms in the lower energy level.
- Simply population inversion is nothing but number of atoms in higher energy level is greater than the number of atom in lower energy level.
- So, if there is a population inversion there by only stimulated emission will able to produce laser beam.
- Population inversion is associated with three Phenomenon.
  - Stimulated emission
  - Amplification
  - Pumping Process
- Stimulated Emission: If majority of atoms are present in higher energy state than the process becomes very easy.
- Amplification: If 'N', represents number of atoms in the ground state and 'N_2' represents number of atoms in the excited state than the amplification of light takes place only when $N_2 > N_1$.

LASER

- If $N_2 > N_1$, there will be a population inversion so induced beam and induced emission are in the same directions and strictly coherent than the resultant laser is said to be amplified.
- Boltzmann's principle gives the information about the fraction of atom found on average in any particulars energy state at equilibrium temperature as
- $\frac{N1}{N2} = \exp(E_2\text{-}E_1/KT) = \exp(\Delta E/KT)$

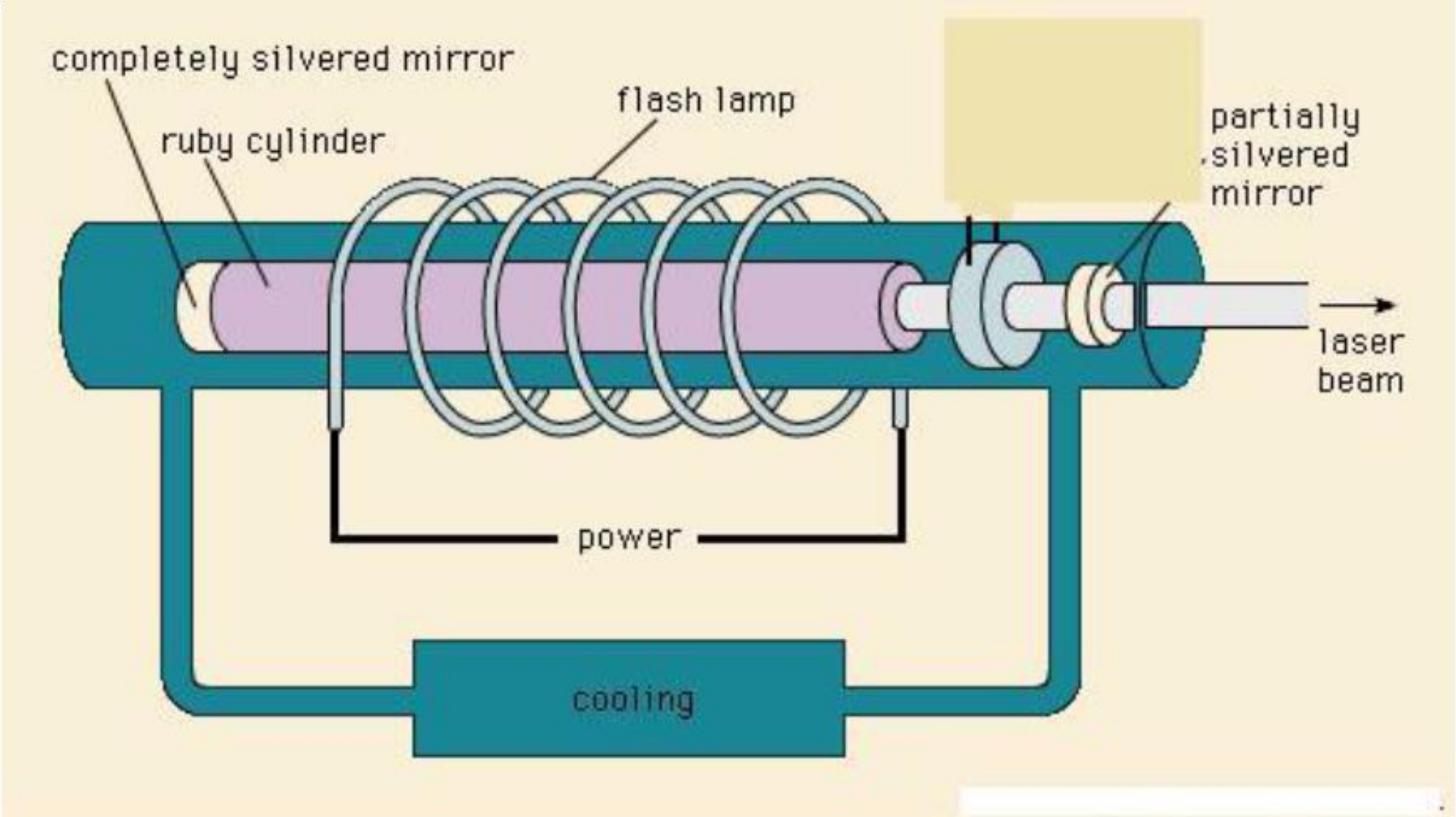
$\frac{N1}{N2} = \exp(hv/KT)$

Pumping Process:

- This process is required to achieve population inversion.
- Pumping process is defined as: "The process which excites the atoms from ground state to excited state to achieve population inversion".
- Pumping can be done by number of ways
- i) Optical Pumping → excitation by strong source of light (flashing of a Camera)
- ii) Electrical Pumping → excitation by electron impact
- iii) Chemical Pumping → excitation by chemical reactions
- iv) Direct Conversion → Electrical energy is directly converted into radiant Energy in devices like LED's, population Inversion is achieved in forward bias.

LASER

- **Ruby Laser:** It is a 3 level solid state laser, discovered by Dr.T.Maiman in 1960.
  <u>Principle:</u>
- The chromium Ions raised to excited states by optical pumping using xenon flash lamp
- Then the atoms are accumulated at metastable state by non-radiative transition.
- Due to stimulated emission the transition of atoms take place from metastable state to ground state, there by emitting laser beam.
- **<u>Construction:</u>**

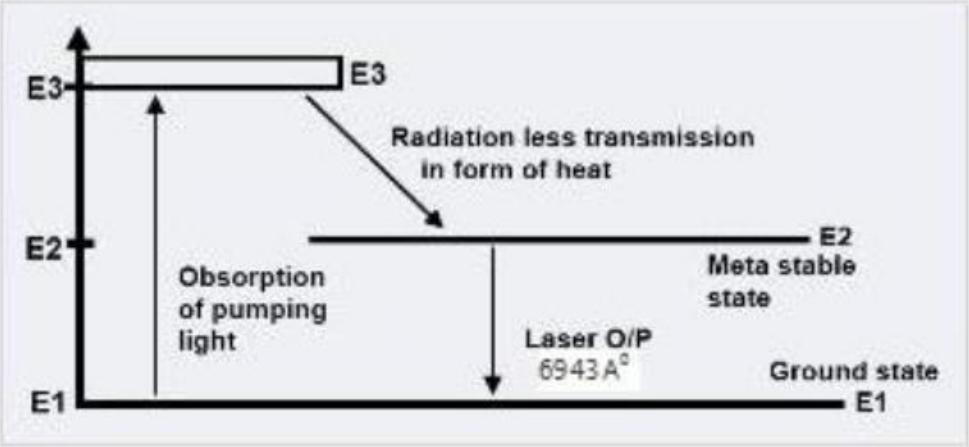


LASER

- Ruby is a crystal of aluminum oxide (Al_2O_3) in which some of the aluminum ions (Al^{3+}) is replaced by chromium ions (Cr^{3+}). This is done by doping small amount (0.05%) of chromium oxide (Cr_2O_3) in the melt of purified Al_2O_3.
- These chromium ions give the pink color to the crystal. Laser rods are prepared from a single crystal of pink ruby. Al_2O_3 does not participate in the laser action. It only acts as the host.
- The ruby crystal is in the form of cylinder. Length of ruby crystal is usually 2 cm to 30 cm and diameter 0.5 cm to 2 cm.
- The ends of ruby crystal are polished, grounded and made flat.
- The one of the ends is completely silvered while the other one is partially silvered to get the efficient output. Thus the two polished ends act as optical resonator system.
- A helical flash lamp filled with xenon is used as a pumping source. The ruby crystal is placed inside a xenon flash lamp. Thus, optical pumping is used to achieve population inversion in ruby laser.
- As very high temperature is produced during the operation of the laser, the rod is surrounded by liquid nitrogen to cool the apparatus.

LASER

- **Working with Energy Level Diagram (ELD):**

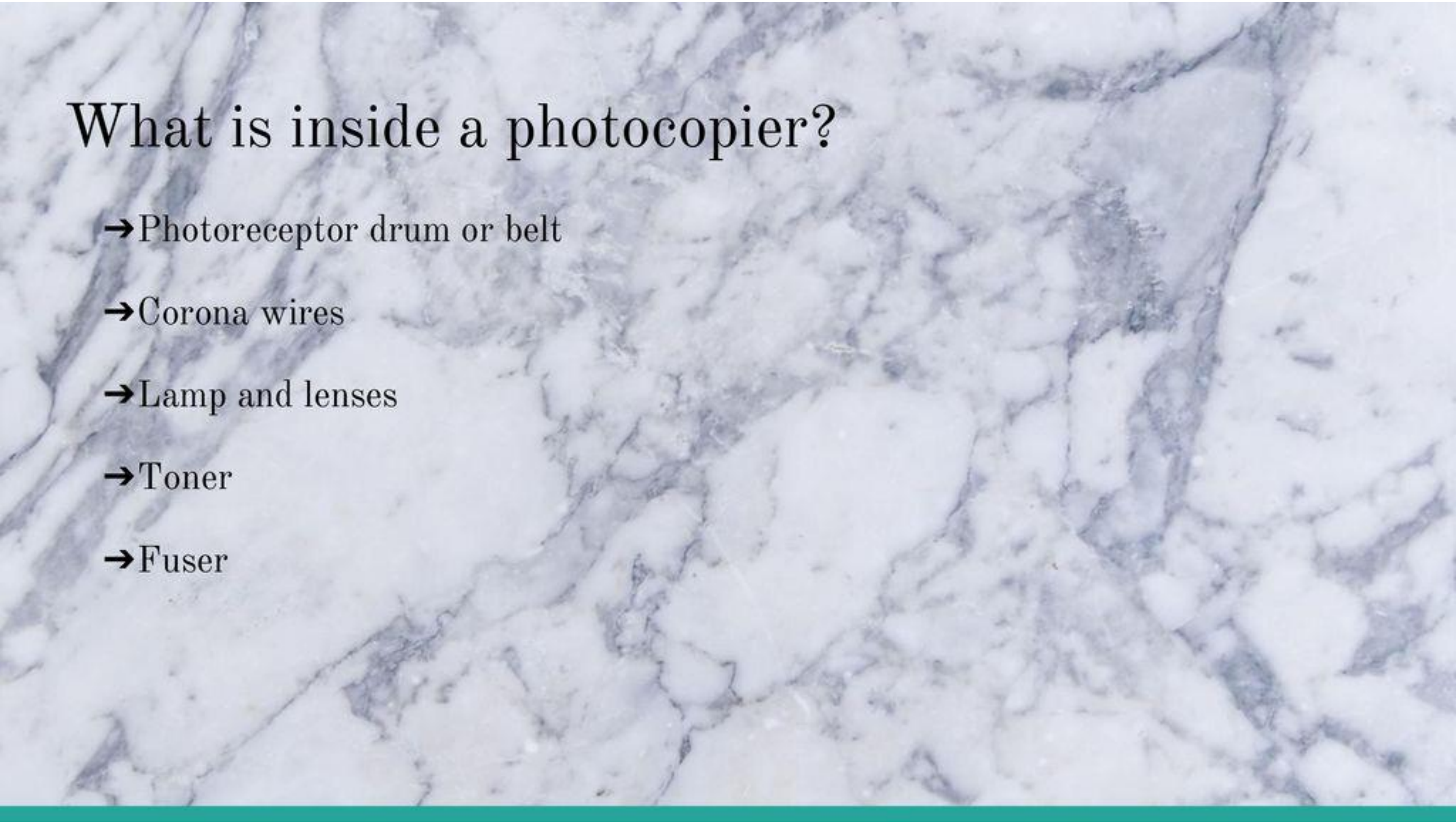


- Fig: Energy Level Diagram of Ruby Laser

- The flash lamp is switched on, a few thousand joules of energy is discharged in a few milliseconds.
- A part of this energy excites the Cr^{3+} Ions to excited state from their ground state and the rest heats up the apparatus can be cooled by the cooling arrangement by passing liquid nitrogen.
- The chromium ions respond to this flash light having wavelength 5600 A^0(Green),[4200 A^0(Red)Also]
- When the Cr^{3+} Ions are excited to energy level E_3 from E_1 the population in E_3 increases.
- Cr^{3+} Ions stay here(E_3) for a very short time of the order of 10^{-8} sec, then they drop to the level E_2 which is metastable state of lifetime 10^{-3} sec .Here the transitions from E_3 to E_2 is non radiative in nature.

LASER

- As the lifetime of the state E_2 is much longer, the number of ions in this state goes on increasing while in the ground state (E_1) goes on decreasing. By this process population inversion is achieved between E_2 & E_1.
- When an excited ion passes spontaneously from the metastable state E_2 to the ground state E_1 it emits a photon of wavelength $6943A^0$.
- This photon travels through the ruby rod and if it is moving parallel to the axis of the crystal, is reflected back & forth by silvered ends until it stimulates an excited ion in E_2 and causes it to emit fresh photon in phase with the earlier photon. This stimulated transition triggers the laser Transition.
- The process is repeated again and again, because the photons repeatedly move along the crystal being reflected from ends. The photons thus get multiplied.
- When the photon beam becomes sufficiently intense, such that a part of it emerges through the partially silvered end of the crystal.



What is inside a photocopier?

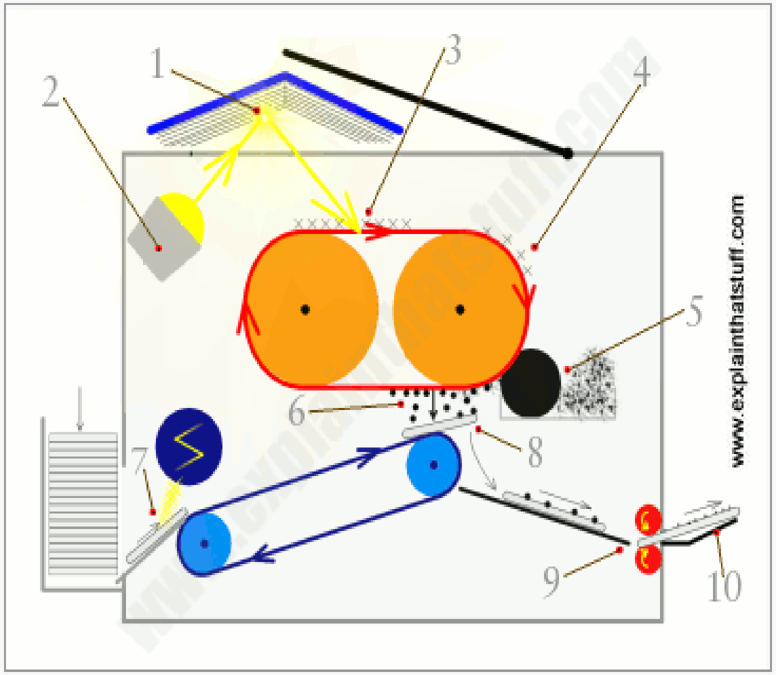
- ➔Photoreceptor drum or belt
- ➔Corona wires
- ➔Lamp and lenses
- ➔Toner
- ➔Fuser

Parts of a photocopier

A typical photocopier (also casually known as a ‘xerox machine’) consists of the following components:

- ✓ **A photoreceptor drum** (or belt), which is covered by a layer of a semiconductor material, such as selenium, silicon or germanium. This is arguably the most critical part of the machine.
- ✓ **A toner**, which is basically just pigmented liquid. Sometimes referred to as ‘dry ink’, a toner is a dry mixture of fine, negatively-charged plastic particles and coloring agents that create the duplicate image on a piece of paper.
- ✓ **Corona wires**, which when subjected to a high voltage, transfer a field of positive charge to the surface of the photoreceptor drum and the copy paper.
- ✓ **A light source** and a few lenses, which shine a bright beam of light on the original document and focus a copy of the image onto a specific place, respectively.
- ✓ **A fuser** can be considered the ‘final’ main component of a photocopier, as a fuser unit melts and presses the toner image onto the copy paper and imparts the final touches to the duplicate image just before it’s ejected from the machine.

How a modern copier works



1. You place the document you want to copy upside down on the glass
2. An extremely bright light scans across the document. Much more light reflects off the white areas (where there is no ink) than off the black, inked areas.
3. An "electrical shadow" of the page forms on the photoconductor. The photoconductor in a photocopier is a rotating conveyor belt coated with a chemical called selenium.
4. As the belt rotates, it carries the electrical shadow around with it.
5. An ink drum touching the belt coats it with tiny particles of powdered ink (toner).
6. The toner has been given an electrical charge, so it sticks to the electrical shadow and makes an inked image of the original page on the belt.
7. A sheet of paper from a hopper on the other side of the copier feeds up toward the first belt on another conveyor belt. As it moves along, the paper is given a strong electrical charge.
8. When the paper moves near the upper belt, its strong charge attracts the charged toner particles away from the belt. The image is rapidly transferred from the belt onto the paper.
9. The inked paper passes through two hot rollers (the fuser unit). The heat and pressure from the rollers fuse the toner particles permanently onto the paper.
10. The final copy emerges from the side of the copier. Thanks to the fuser unit, the paper is still warm. It may still have enough static electric charge to stick to your pullover. Try it (but make sure the ink is dry first).

- **Charge.** Inside every copier and laser printer is a light-sensitive surface called a photoreceptor. It consists of a thin layer of photoconductive material that is applied to a flexible belt or drum. The photoreceptor is insulating in the dark, but becomes conducting when it is exposed to light. It is charged in the dark by applying a high DC voltage to adjacent wires, which produces an intense electric field near the wires that causes the air molecules to ionize. Ions of the same polarity as the voltage on the wires deposit on the photoreceptor's surface, creating an electric field across it.
- **Expose.** In a digital copier or printer, the image is exposed on the photoreceptor with a scanning modulated laser or a light-emitting-diode image bar. In older analog copiers, reflected light from an illuminated image is projected onto the photoreceptor. In either case, the areas of the photoreceptor exposed to light are selectively discharged, causing a reduction in the electric field. The darker areas retain their charge.
- **Develop.** Pigmented powder used to develop the image is called toner. Toner particles made of colorant and plastic resin have precisely controlled electrostatic properties and range from about five to 10 micrometers in diameter. They are mixed with and charged by magnetized carrier beads that transport them to the development zone. The particles are charged by the phenomenon of triboelectricity (often referred to as static electricity). The electric field associated with the charge pattern of the image on the photoreceptor exerts an electrostatic force on the charged toner, which adheres to the image. A color document is formed by a printer with four separate xerographic units that create and develop separate cyan, magenta, yellow and black images. The superposition of these powder images produces full-color documents.
- **Transfer.** The powder image is transferred from the photoreceptor onto paper by bringing the paper in contact with the toner and then applying a charge with polarity opposite to that of the toner. The charge must be strong enough to overcome the powders adhesion to the photoreceptor. A second precisely controlled charge releases the paper, now containing the image, from the photoreceptor.
- **Fuse.** In the fusing process, the toner comprising the image is melted and bonded to the paper. This is accomplished by passing the paper through a pair of rollers. A heated roll melts the toner, which is fused to the paper with the aid of pressure from the second roll.
- **Clean.** Toner transfer from the photoreceptor to the paper is not 100 percent efficient, and residual toner must be removed from the photoreceptor before the next print cycle. Most medium- and high-speed copiers and printers accomplish this with a rotating brush cleaner.

Xerography is a unique process that depends on chemical, electrical, mechanical and software know-how. The rap

OPTICAL PROPERTIES

Interaction of Light with Materials

Consider a monochromatic light of wave length λ is incident on a glass material as shown in Fig. 13.2. Let I be the intensity of the incident light. When a light incident at the air-glass interface, a part of the light gets reflected back while a part of the light transmitted into the glass materials. The transmitted light in the glass material interacts with atoms, molecules, ions and charged particles present in the materials. As a result, a small part of the transmitted light is observed by the glass materials. When the transmitted light reaches the other end of the glass, it is again transmitted at the glass-air interface.

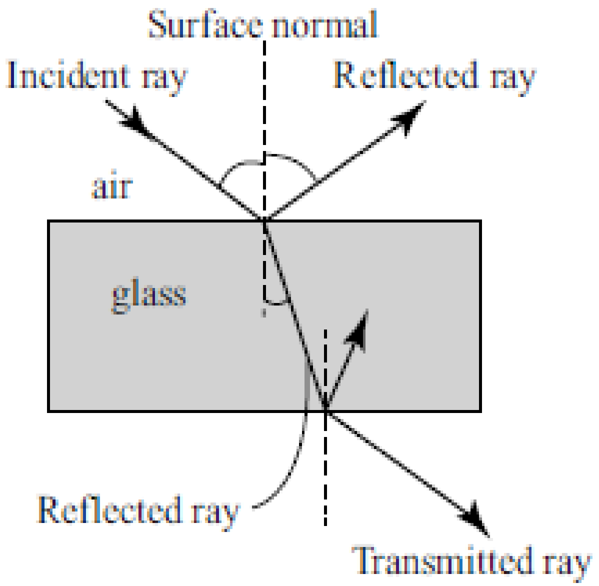


Fig. 13.2 *Transmission of Light*

OPTICAL PROPERTIES

Interaction of Light with Materials

Let I_r, I_a and I_t be the intensity of reflected, absorbed, and transmitted light respectively. Therefore, the intensity of incident light

$$I = I_r + I_a + I_t \qquad (13.3)$$

Dividing the above equation by I, we get

$$\frac{I_r}{I} = \frac{I_a}{I} = \frac{I_e}{I} = 1 \qquad (13.4)$$

where $R = \frac{I_r}{I}$, $A = \frac{I_a}{I}$ and $T = \frac{I_e}{I}$ is known as *reflectivity*, *absorptivity* and *transmitivity*.

It is clear from the above discussion that when an electromagnetic radiation, i.e., light is incident on optical materials, the phenomena like scattering, refraction, reflection, transmission, absorption and luminescence takes place due to the interaction of light with electron.

OPTICAL PROPERTIES

Atomic and Electronic Interactions

The interaction between the electromagnetic radiations and the atom, ions or electrons leads to several optical phenomena in materials. The most important interactions are electronic polarisation and electron energy transfer.

(1) ***Electronic polarisation*** When an electric field is applied to a solid material, the electronic field interacts with electron clouds surrounding each atom. As a result, atoms are shifted through a small distance relative to the nucleus in a direction opposite to the field direction. Thus, it creates a dipole and hence, induces polarisation. The induced polarisation may result in two effects namely, the absorption of energy of the incident radiation and a reduction in the velocity of the light when it passes through the material. In most of the optical materials, the second effect is more dominant and is discussed as refraction.

(2) ***Electron transition*** One can explain the phenomena of absorption and emission of electromagnetic radiation by considering transition of electron when a light radiation is incident on material. Consider that an electromagnetic light of frequency ν is incident on the material. The atoms in the ground state (E_1) absorb energy and hence, it is excited to the higher energy state E_3. The process of absorption and radiation of electromagnetic radiation is shown in Fig. 13.3.

OPTICAL PROPERTIES

Atomic and Electronic Interactions

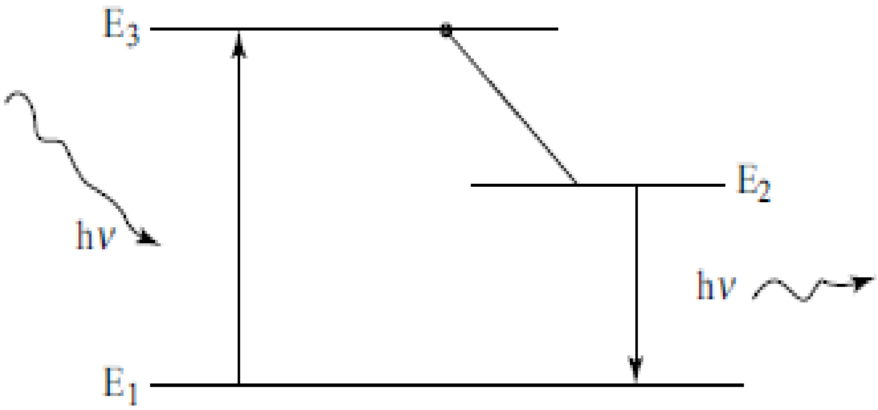


Fig. 13.3 *Electron transition – Absorption and emission*

This electron transition is possible only if the energy of the photon is equal to the difference in the energy levels of the filled (E_1) and excited states (E_3).

i.e., $\Delta E = E_3 - E_1$

or, Energy of photon $E = \Delta E = h\nu$ (13.5)

The excited electrons cannot be stable for a long period of time in E_3 being as an unstable state. Hence, it will be lifted to a new state known as intermediate whose energy lies between E_3 and E_1. The electron from intermediate state is returned back to the ground state E_1 with the radiation energy $h\upsilon$.

OPTICAL PROPERTIES

Atomic and Electronic Interactions

LUMINESCENCE